Local freshwater and carbon impact of electric mobility

Developing a methodology to assess the local freshwater and carbon impact of using electric vehicles

Master thesis Energy Science
30 ECTS

Daan van Put (3953977)
Marlinde Knoope
Ernst Worrell

24th February 2016, Utrecht

Utrecht University

Summary

The use of electric transportation is growing rapidly. The global electric vehicle (EV) stock reached over 1,2 million vehicles in 2015, which is almost seven times the stock in 2012. It is expected that this increase will continue in the coming decades. The use of EVs, however, can have a significant freshwater and carbon impact as a result of the production of the required electricity. In times when freshwater is becoming a scarce resource in multiple regions worldwide, a methodology is required to assess to local impact of EV usage. This study has developed a methodology to assess the freshwater and carbon impact of EV usage in a region, based on the local electricity mix and water scarcity. The methodology is demonstrated by implementing it to California (United States), Rajasthan (India) and the Netherlands.

Based on the findings in this study it can be concluded that the local freshwater impact of EV usage is small in most regions, even when 50% of the existing passenger car fleet is electric. In regions with a large existing freshwater footprint, which is often a result of intensive agriculture, the relative contribution of EV usage to the total freshwater consumption is only minimal. This can be seen in California and Rajasthan, where an EV deployment of 50% leads to a freshwater consumption of less than 0,5% of the total annual freshwater consumption. In regions with a lower existing freshwater footprint the relative impact of EV usage is much larger, which can be seen in the Netherlands. However, in the Netherlands freshwater scarcity is low, resulting in no problematic impact of EV usage. Only in regions with a small existing water footprint in combination with high existing water scarcity, EV usage is expected to significantly contribute to more local freshwater scarcity.

The local carbon impact of EV usage strongly depends on the region. In Rajasthan the CO_2 intensity of EVs is 171 g/km, while in California and the Netherlands the intensity is only 44 g/km and 85 g/km, respectively. Variations are the result of differences in the efficiency and composition of the local electricity mix. Decreasing the carbon impact of the electricity mix, however, can result in a significant increase of the freshwater impact. The average freshwater consumption of geothermal generators, for example, is almost four times higher than the average consumption of fossil fuelled generators. The freshwater consumption of hydroelectric generators is even more than 10 times higher. Therefore, a small carbon impact of EV usage does not inherently mean that the freshwater impact is also small.

Contents

1. Introduction

The use of electric transportation is growing rapidly. The number of electric passenger vehicles (EVs) on the Dutch roads is currently more than twice the number of January 2015 (RVO, 2017). By January 2017 there were over 98,000 EVs registered in the Netherlands, which is a market share of just over 1 percent (RVO, 2017; CBS, 2017a). This number includes all EVs that have to be charged externally (Yong, Ramachandaramurthy, Tan, & Mithulananthan, 2015). But not only in the Netherlands is the use of EVs growing. The global EV stock in 2015 was about 1.2 million cars, which is about seven times more than the stock in 2012 (IEA, 2016). Most of these cars are registered in developed countries like the United States, the Netherlands and Norway. However, also in upcoming economies like China and India there is a rapid growth in the number of EVs (IEA, 2016). Expectations diverge strongly, but the global EV stock might reach 100 million cars in 2030 (IEA, 2016).

One of the reasons for the popularity of EVs is that electrified transportation is a promising to alleviate the climate change issue (Steinhilber, Wells, & Thankappan, 2013; Yong et al., 2015). Therefore, it is supported and stimulated by the governments of many countries (IEA, 2016). The well-to-wheel emissions of an average passenger vehicle can be reduced from about 150 g/km when using a gasoline car, to less than 60 g/km when using a full EV with the average European electricity mix (Edwards et al., 2013). The emissions of a full EV even approaches zero when electricity is produced with sustainable energy sources like wind and solar energy (Edwards et al., 2013). Besides that, the tailpipe emissions of EVs are always zero which can help to reduce air pollution in crowded areas (Yong et al., 2015). However, there is also a downside to the use of electrified transportation which is not discussed often, but might affect the opinion towards EVs. This is the fact that there are high water requirements for driving an EV (Schornagel, Niele, Worrell, & Böggemann, 2012; King & Webber, 2007)

The high water needs for driving an EV is a result of the water requirements for producing electricity. A research of (Averyt et al., 2011) showed that the power sector is one of the largest water users of all sectors in the United States. The power sector uses water for multiple purposes, like resource extraction, generating steam and cooling systems (Macknick, Newmark, Heath, & Hallett, 2011). King & Webber (2007) demonstrated that as a result of this, electric miles powered by the average electricity mix in the United States withdraw over 17 times more water and consume almost 3 times more water than miles powered by gasoline. The withdrawal of freshwater, which is the extraction of freshwater from the local environment, can be problematic as a result of existing water scarcity (Global reporting initiative, 2010). The consumption of water, which is the usage of water in such a way that it is not available to the local environment anymore, can contribute to even more water scarcity (Bayart et al., 2010). The availability of freshwater of sufficient quality is an important issue on present policy agenda's because many regions all over the world face freshwater scarcity problems (Mekonnen, Gerbens-Leenes, & Hoekstra, 2015). The World Economic forum even indicates water crises as the single largest global risk in terms of potential impact (WEF, 2015). Therefore, it is very important to compare the freshwater requirements for using EVs with the freshwater characteristics in a specific region, before implementing EVs.

Several studies regarding the water impact of EVs already exist, like (Schornagel et al., 2012) and (Mekonnen et al., 2015). However, these studies focus on global averages, while the actual freshwater requirement for using EVs is highly dependent on the local electricity mix. This makes global averages inappropriate for local assessments (Averyt et al., 2011). Besides that, the consequences of freshwater usage differ per region. In regions with an abundant freshwater availability large freshwater usage might be no problem, while in regions with high water scarcities a small increase in freshwater usage might be catastrophic. This stresses the need for a method to assess the freshwater impact of using EVs for individual regions. Several methods to assess the water usage of products and services already exist, like the Water Footprint Assessment Manual (WFAM) (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011) and the Life Cycle Assessment (LCA) (Pfister, Koehler, & Hellweg, 2009). The WFAM, however, gives absolute numbers on water requirements and does not compare these with local water availability. LCAs do give the opportunity to look at the relation with the local water availability, but in LCAs absolute numbers of water consumption are multiplied with the water stress index in a specific region. In this way relative results are created which are useful to make comparisons between regions, but cannot be used for making statements about individual regions (A. Y. Hoekstra, 2016). Because of the shortcomings of existing studies and methods, it is necessary to develop a new method which can be used to assess the impact of using EV in a specific region.

This study tries to fill the gap in in literature by developing a methodology which includes local aspects about EV usage, electricity production and water scarcity. Because EV usage is often stimulated to reduce emissions in a region, it is also important to incorporate the carbon impact of using EVs in the methodology. In this way a complete overview of the local impact of using EVs can be given. Therefore, this research will answer the following research question:

What is the local freshwater and carbon impact of implementing electric vehicles in a region, taking into account the local electricity mix and water scarcity?

To give an answer on the research question this study consists of two parts. In the first part the methodology is developed for doing the assessment of the local impact of using EVs. The methodology can be used by both governments and companies. Governments can use the result to decide on their policies regarding EVs and electricity production. Companies can use the result to assess the impact of their products and to find market opportunities in specific regions. In the second part the methodology will be demonstrated by applying case studies to three regions with ambitious EV deployment targets and distinguishing characteristics regarding water availability or electricity production; California (United States), Rajasthan (India) and the Netherlands.

In this report first the required background information for assessing the impact of EVs is provided in chapter 2. Subsequently, in chapter 3, the developed methodology is described, explained and underpinned elaborately. In chapter 4 the collected data of the three case studies is presented, followed by the results of the case studies in chapter 5. Chapter 6 provides the discussion of both the developed methodology and the results of the case studies. Finally, in chapter 7, the conclusion will be presented of what the local freshwater and carbon impact is of using EVs, based on the outcomes of the three case studies.

2. Background information

2.1 Human water usage

For almost all human activities water is required. The salinity of used water and the type of water usage determine the impact of human water usage on the local environment. To investigate the relation between EV usage, water usage and water scarcity, some background information on human water usage is essential.

2.1.1 Salinity of water

Salinity is the first general characterization of water quality and is usually expressed as total milligram dissolved solids (TDS) per litre of water (van Weert, van der Gun, & Reckman, 2009). A categorization can be made into four salinity classes; freshwater, brackish water, saline water and brine. Multiple TDS ranges for these classes exist, but the ranges used most often are presented in table 1.

Table 1: Categorization of water types based on their salinity, including the TDS ranges.

Type	TDS range (in mg/l)
Freshwater	0 - 1,000
Brackish water	1,000 – 10,000
Saline water	10,000 – 100,000
Brine	> 100,000

Reference: van Weert et al. (2009).

By far most water on earth is saline water, which can be found in seas and oceans. 97% of the earth's water is saline, only 2,5% is fresh (Gleick, 1996). Freshwater can be found in lakes, rivers and groundwater, and is, stored in icecaps and glaciers. At locations where saline and freshwater mix up, brackish water occurs, as in estuaries, mangroves and some seas. Besides that, saline, brackish and fresh water may occur in fossil aquifers (Gleick, 1996). Freshwater is the most important natural resources for humans (Hoekstra et al., 2011). The possibility to use either saline or brackish water for human purposes is limited. Only in mining and industrial processes some purposes exist for the large scale usage of saline water (USGS, 2016a). It is possible to turn saline and brackish water into fresh water by a process called desalination. In that process thermal energy or membranes are used to desalinate water, resulting in freshwater and brine (Tsiourtis, 2001). Brine is highly saline water which is mainly a reject of human activities, but can also be found as natural resource in aquifers at limited locations (van Weert et al., 2009). Desalination, however, is associated with high capital costs, high-energy consumption and very high unit cost compared to conventional water. Besides that, saline water is only available at the coast and mitigation measures are required to prevent the rejected brine from polluting the local ecosystem (Tsiourtis, 2001). Despite the downsides, technical developments and increasing water scarcities have resulted in an increasing use of desalination, especially in the Middle East (IDA, 2016).

2.1.2 Freshwater usage

Freshwater is the most important natural resources for the survival of almost all ecosystems. Humans use freshwater for drinking, cooking, washing, field irrigation and industrial processes. Spatial differences exist in the share of different purposes to the total water usage. In most developing countries agriculture accounts for more than 90% of the water withdrawals, while in most developed country almost 60% of the withdrawals are for industry (Growing Blue, 2011). A distinction is made between three components of freshwater usage; blue, green and grey water usage (Hoekstra et al., 2011). Blue water usage refers to the usage of fresh runoff water, mainly from groundwater or rivers, for the production of a good or service. Green water usage refers to the direct usage of rainwater, mainly through the uptake of soil water, during the production process of a good. Grey water usage refers to the amount of water that would be required to dilute degraded water so that it just meets agreed water quality standards (Schornagel et al., 2012). The term grey water, however, is debatable because it seems to justify the dilution of heavy polluted water instead of reducing its emission (Hoekstra et al., 2011).

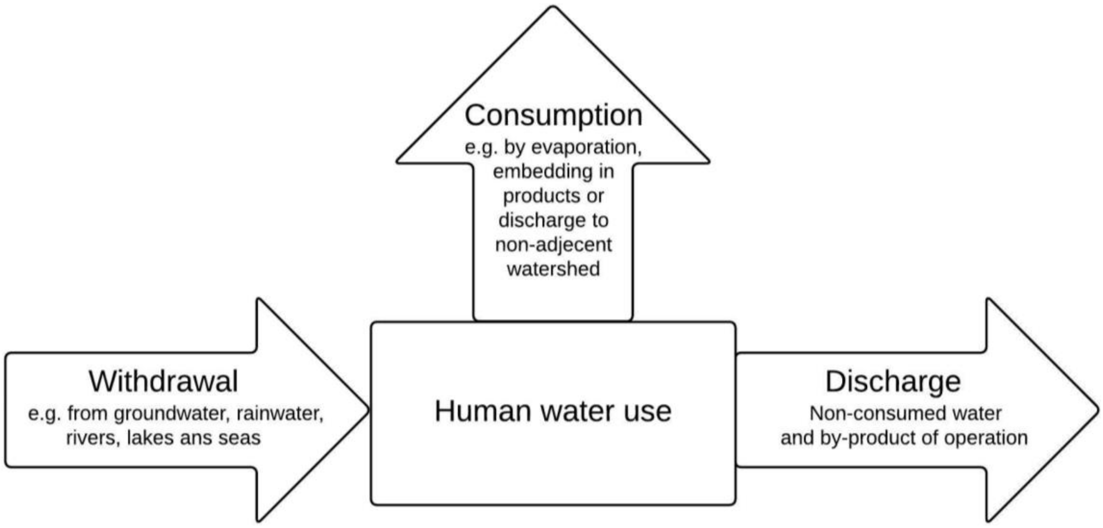


Figure 1: Difference between water withdrawal, consumption and discharge (based on Schornagel et al., 2012; Hoekstra et al., 2011)

The term water usage is too general to define its impact on the local environment. As described briefly in the introduction, the term water usage includes both water withdrawal and consumption, which have a different impact on the environment (Schornagel et al., 2012). The different processes are visualized in figure 1. The term water withdrawal is defined as the freshwater removed from the local environment for human purposes (Macknick et al., 2011). This can be every type of water, like, groundwater, rainwater or water from rivers or lakes. For saline water the term intake is often used instead of withdrawal to describe the extraction of ocean water. When water is withdrawn it can be either consumed or discharged. Water consumption means that the water is used in such a way that it is not released to the same watershed as from where it was withdrawn (Bayart et al., 2010). This does not mean that the water disappears, because water will remain within the water cycle and always return somewhere. However, it is not directly useful for the local environment anymore. Water can be consumed in four different ways (Hoekstra et al., 2011):

- Water evaporates.
- Water is incorporated into a product, for example, in agricultural crops.
- Water does not return to the same catchment area, for example, it is returned to another catchment area or the sea.
- Water does not return in the same period, for example, it is withdrawn in a scarce period and returned in a wet period.

Water discharge includes all water that is released to the same watershed as from where water was withdrawn. This means that it includes all withdrawn water that is not consumed, but can also include water that is a by-product of the operation itself, say, from a chemical reaction or the processing of succulent biomass (Schornagel et al., 2012).

2.1.3 Freshwater scarcity

Although fresh water is continuously replenished through the water cycle, its availability is not unlimited. When regional freshwater demand becomes a significant share of the availability, the threat of freshwater scarcity arises (Hoekstra et al., 2011). This phenomenon can be seen in multiple regions worldwide. Due to growing world population and alternating precipitation patterns it is expected that freshwater scarcities will rise strongly in the future. The World Economic forum even indicates water crises as the single largest global risk in terms of potential impact (WEF, 2015).

Multiple definitions for water scarcity exist. An often used definition of water scarcity is the water withdrawal in a region compared to the total water availability, also called the water-to-availability (WTA) index or water scarcity index (WSI) (Falkenmark et al., 2007; Kundzewicz et al., 2007; Wada et al., 2011). The index indicates moderate or looming water scarcity as index value between 0,2 and 0,4, severe or actual water scarcity as a value between 0,4 and 0,8, and high or economically debilitating water scarcity as index values reaching over 0,8 (Kundzewicz et al., 2007; Falkenmark et al., 2007). Kundzewicz et al. (2007) adds that severe water scarcity occurs when water availability per capita is less than 1000 m^3/year and high water scarcity when water availability per capita is less than 500 m^3/year.

More recent studies focus on the consumption of water instead of the withdrawal, compared to water availability, also called the consumption-to-availability (CTA) index. Examples of studies using the CTA index are studies of Hoekstra et al. (2012) and A. Hoekstra (2016). In these studies it is stated that focusing water scarcity on consumption is more convenient because most withdrawn water becomes available for reuse after it is discharged to local rivers and aquifers. In agriculture, for example, 40% of withdrawals typically become available for reuse, in industries and households even 90-95%. Only when water is consumed and is not available for the local environment anymore, it contributes to local water scarcity. Activities that have high water withdrawals can only suffer from existing water scarcities. In the studies of Hoekstra et al. (2012) and A. Hoekstra (2016) the impact of blue water consumption is compared to the blue water availability. They state that river flows require at least 80% of the natural runoff to not increase risks to ecological health and ecosystem services. Therefore, when the CTA index reaches over 20% first moderate blue water scarcities arise. With an index over 30% significant scarcities arise and an index over 40% leads to severe blue water scarcities.

2.2 Electric mobility

To investigate the impact of growing EV usage, estimations have to be made about future EV deployment and the electricity that is necessary to charge EVs. To make these estimations some background information about electric mobility is useful. This chapter describes briefly what types of EVs currently exist and what the international trends in EV usage are.

2.2.1 Types of EVs

Different types of EVs are currently available on the market. This report, and the methodology developed in this study, is only applicable to EVs with a battery that can be charged directly with electricity from the grid. This means that this report is not relevant for full hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs), because the battery of HEVs can only be charged internally by the built-in internal combustion engine, and the engine of FCEVs is fuelled with hydrogen (IEA, 2016; Yong et al., 2015). There are currently three types of vehicles available that do have the possibility to be charged directly with electricity from the grid; full electric vehicles (FEVs), electric vehicles with range extender (E-REVs) and plug-in hybrid electric vehicles (PHEVs). A brief description of these three types is given below (Yong et al., 2015).

- A full electric vehicle (FEV) only uses an electromotor to drive its shaft. The electromotor gets its power form a battery which can be charged externally by means of a plug. Mostly, the battery is provided with extra power during driving by using an RB system. An RB system converts kinetic energy into chemical energy during braking which can be stored in the battery (Yong et al., 2015). The capacity of the battery differs per model and is the largest determinant for the range of the car. The battery of a Nissan Leaf, as example, has a capacity of 30 kWh, which results in a range of between 125 and 200 km, depending on weather, road and driving characteristics (Nissan, n.d.). The battery of the Tesla model S is significantly larger with a capacity of 70 to 90 kWh, resulting in a range of over 500 km (Tesla, n.d.).

- An Electric vehicle with range extender (E-REV) is also propelled by an electromotor only which gets its power from a battery. This battery can also be charged externally and by means of an RB system. However, the battery of an E-REV can also be charged by means of an on board electricity generator; the range extender. The range extender is usually powered by a conventional internal combustion engine (ICE), whereby the battery can be charged while driving (Yong et al., 2015). This significantly extends the range of the car, but also results in considerably more emissions of greenhouse gasses (Idtechex, 2015). An example of an E-REV model is the BMW i3 REX, which is also available in a full electric model. The full electric model has a battery of 19 kWh, resulting in a range up to 160km. Due to the range extender the range of the BMW i3 REX is almost double (BMW, n.d.). However, there is only a small offer of E-REV models and the market share is negligible compared to the number of FEVs or PHEVs. Therefore E-REVs are often combined with PHEVs in charts and overviews of EV implementation (IEA, 2016; RVO, 2017).

- A Plug-in hybrid electric vehicle (PHEV) can be driven by both an electromotor and an internal combustion engine (ICE). When driving on the electromotor the propulsion of a PHEV is comparable to an FEV. However, the propulsion of a PHEV can switch completely to an ICE when the battery runs out of electricity (Yong et al., 2015). The capacity of the battery in a PHEV is often significantly smaller than an FEV due to the possibility to switch to the ICE. The capacity of the battery of a Chevrolet Volt, as an example, is only 18.4kWh, resulting in a range of only about 85km. However, when including the ICE the range increases up to about 675km (Chevrolet, 2016).

2.2.2 Trends in EV usage

In 2015 the global EV stock reached a milestone of 1 million cars. This is remarkable because in 2011 the global EV stock consisted of only 60 thousand cars, which means that since that year the car stock on average has more than doubled each year (IEA, 2016). The main reasons for this rapid increase are the improved EV technology (e.g. energy density of batteries), a larger availability of EV support equipment (e.g. charging stations) and increased policy support (IEA, 2016). Figure 2 visualizes the trend of the EV stock in the past six years and distinguishes per type of EV and country.

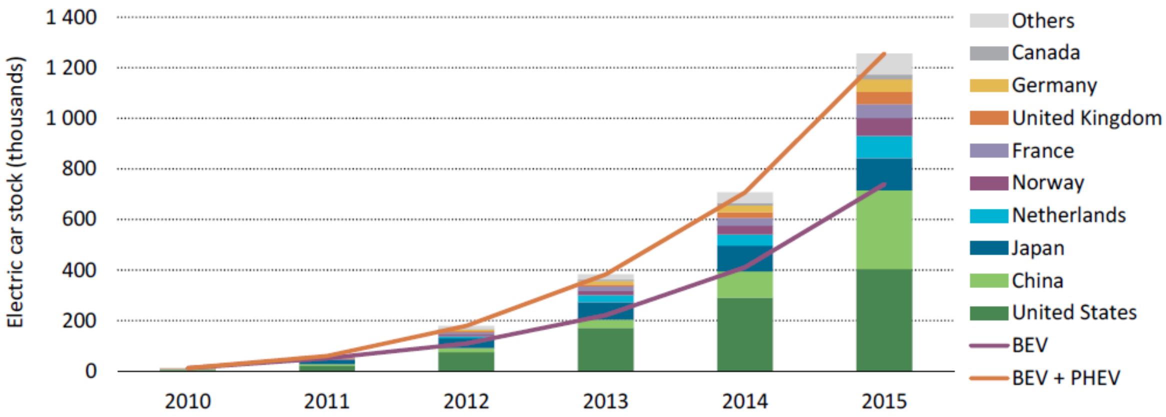


Figure 2: Trend of the global EV stock in the past six years per type of EV and per country. The number of E-REVs is included in the number of PHEVs (IEA, 2016).

Although EV usage is growing rapidly, the share of EVs is still only 0,1% of the global passenger vehicle stock (IEA, 2016). In the climate agreement of the 2015 United Nations Climate Change Conference (COP21), the objective is set to limit the global average temperature increase below 2°C (IEA 2DS). To reach this target it is necessary to decrease the greenhouse gas (GHG) emissions of the transport sector by 18% (UNFCCC, 2015). One way to decrease the emissions is to increase the share of EVs way beyond its current 0,1%, which encouraged multiple agencies to set ambitious EV targets. The 20 by 20 target of the Electric Vehicle Initiative (EVI), for example, aims for a global EV fleet of 20 million by 2020 (CEM, 2016). The Paris Declaration on Electro-Mobility has set a global deployment target of 100 million EVs in 2030 (UNFCCC, 2015). Besides that, also individual countries have set targets for their future EV fleet. Interesting is that not only the current leading countries in EV deployment have set national targets, but also upcoming economies like India. India strives for a car fleet of 300,000 cars in 2020, which is 50 times more than their current fleet (IEA, 2016). However, the cumulative country targets still do not add up to the aimed 20 million cars in 2020. An overview of the global targets and deployment scenarios is visualized in Figure 3.

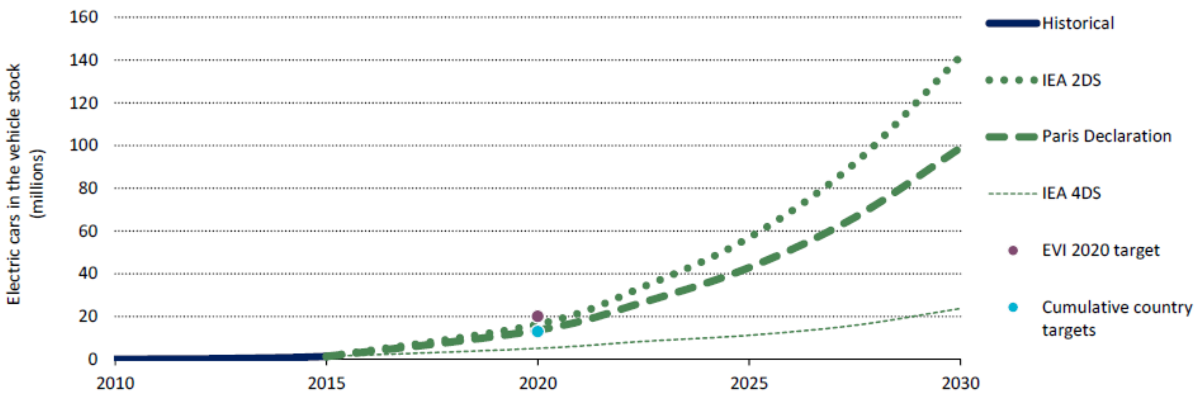


Figure 3: Deployment scenarios and targets for the global EV stock to 2030 (IEA, 2016)

2.2.3 Efficiency of EVs

Existing literature demonstrates the efficiency of EVs compared to conventional cars because of their efficient power train and electromotor, resulting in less lifecycle greenhouse gas emissions (Yong et al., 2015). However, the impact of the total EV fleet depends on the share of FEVs, PHEVs and E-REVs. PHEV and E-REV owners still have the opportunity to propel their car with fossil fuels, while FEV owners can only propel their car with electricity. This difference strongly affects the number of kilometres propelled by electricity from the grid. Research of Axsen & Kurani (2010) shows that PHEV owners in California on average use their electromotor only 50% of the time. In the other 50% of the time the ICE is used so fossil fuels are consumed instead of electricity from the grid. The current global EV stock consists for about 60% of FEVs and for about 40% of PHEVs and E-REVs, which can be seen in figure 2. However, strong differences between these shares can be found in different countries, which is visualized in figure 4. In Norway about 80% of the EV stock consists of FEVs, while in the Netherlands about 90% consists of PHEVs and E-REVs.

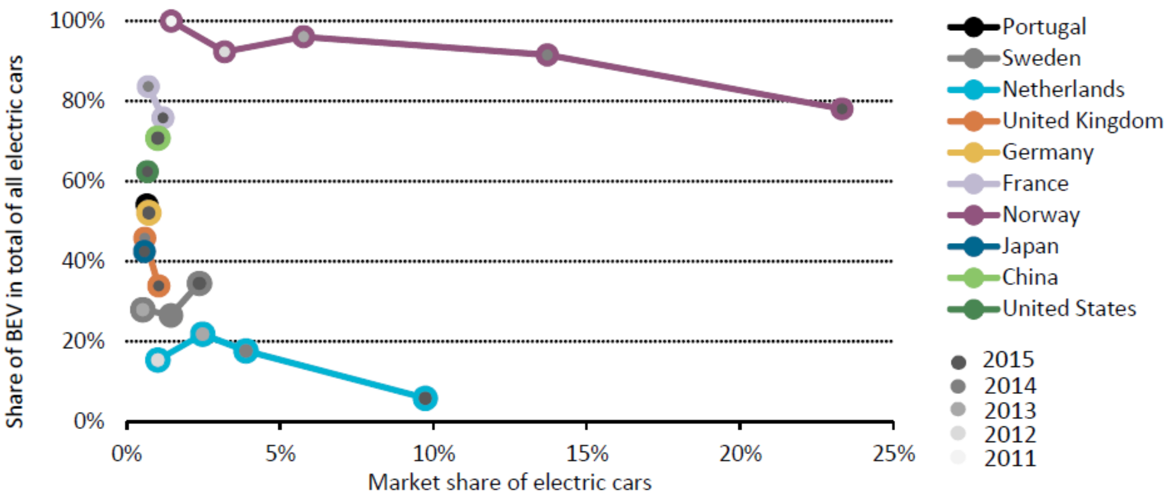


Figure 4: Evolution of the FEV share (named battery electric vehicles (BEVs) in this figure) against the total EV market in selected countries. Countries with EV market shares below 1% are shown only for the most recent year (IEA, 2016).

Besides the type of EV, also the ambient temperature influences the efficiency of EVs. Yuksel & Michalek (2015) demonstrate that the efficiency of EVs decrease drastically at low or high ambient temperatures. At low temperatures this is a result of decreasing battery efficiency and discharge capabilities. At high temperatures batteries are more efficient but also degrade faster. To avoid fast degradation energy intensive cooling equipment is installed which far outweighs the positive effect of the efficiency increase. Besides that, extreme weather conditions result in an increased energy demand for cooling and heating. The latter also applies to conventional cars but energy consumption for heating EVs is significantly larger because no waste heat from the engine can be used. Overall, data of Fleetcarma (2014) shows that the efficiency of EVs is highest in an ambient temperature between 15°C and 25°C, but can decrease almost 40% in extreme weather conditions.

2.3 Electricity production

Electricity that is required for driving EVs has to be produced by electricity generators. Many different types of generators exist and the composition of the electricity mix in a region determines the carbon and water impact of EV usage. A brief overview of different types of electricity generators is useful to understand the impacts.

2.3.1 Generation technologies

Mostly, generation technologies are categorized based on the sustainability of their electricity production, which is defined by the renewability of the input fuel. Renewable energy sources are theoretically inexhaustible and include bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy and wind energy (Edenhofer et al., 2014). Non-renewable energy sources are defined as theoretically exhaustible and include fossil and nuclear energy. Fossil energy is based on all types of coal, oil and natural gas, nuclear energy is based on uranium (Edenhofer et al., 2014). The input fuel is the largest determinant for the carbon impact of operating electricity generators. On average, the carbon impact of generators using renewable and nuclear energy is lower than the impact of generators using fossil energy (Sathaye et al., 2011; Moomaw et al., 2011). Besides that, the carbon impact is determined by the efficiency of electricity generators. For fossil energy, on average natural gas fuelled generators are more efficient than coal and oil fuelled generators (Hussy, Klaasen, Koornneef, & Wigand, 2014). The current and expected future global electricity production per input fuel is displayed in Figure 5. It can be seen that mainly the share of renewable and natural gas production is expected to increase significantly in the coming decades (EIA, 2016a)

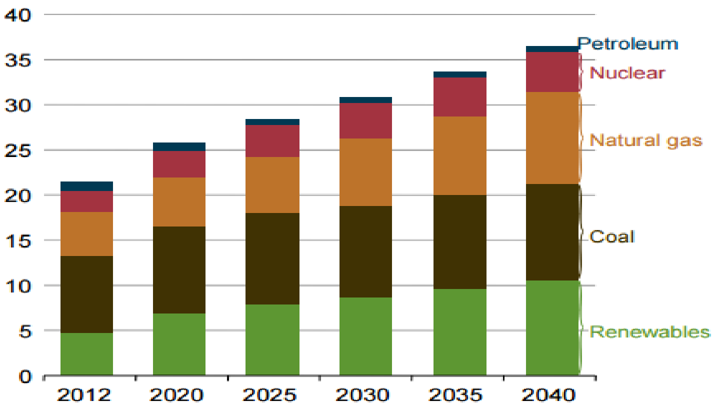


Figure 5: World net electricity generation by energy source in trillions kWh (EIA, 2016a).

The water impact of operating electricity generators is mainly determined by the configuration technology of generators (Macknick et al., 2011). In this study a distinction is made between three types of generators; wet thermal generators, dry thermal generators and non-thermal generators. Wet thermal generators include all generators that use heat to turn water into steam, which passes through a steam turbine to generate electricity. Heat can be provided by the combustion of fossil fuels and biomass, or by nuclear energy, geothermal energy and concentrated solar power (CSP). The generators are defined as wet because water is required both as working fluid and, in most cases, as cooling fluid. Besides that, for some technologies water is required for cleaning purposes (Macknick et al., 2011).

Dry thermal generators produce heat to generate electricity, but do not require any water during this process. The only electricity generators that fall within this category are combustion turbines (Power Engineering, 2014). Combustion engines are a well-known technology used in vehicles to covert chemical energy into rotational energy and can be fuelled with natural gas, oil and biofuels. In recent years combustion turbines are also used more often for the purpose of large scale electricity production (Wärtsilä, 2016). Combustion turbines are mainly used to provide the required flexibility when many intermittent renewable energy sources are installed. Combustion engines are very suitable for this because they have a fast start up time and high part-loading efficiency. Combustion engines do not use any water because the 'closed loop radiator cooling' eliminates the need for water (Power Engineering, 2014). Combustion turbines can easily be built at scales of 300 to over 500 MW by combining multiple units; the largest plant in the world using combustion turbines is 573

MW. However, most combustion turbines currently installed are smaller. The largest in Europe is 250 MW, the largest in California 207 MW (Power Engineering, 2014; CEC, 2016).

Finally, non-thermal generators include all generators which do not produce heat to generate electricity. This includes hydroelectric generators, wind turbines, photovoltaic (PV) panels and generators producing electricity from ocean energy. Because these generators do not use heat for electricity production, no water as working or cooling fluid is required (Macknick et al., 2011). However, this does not mean that non-thermal generators do not use any water. Mainly hydropower has a large water impact because of evaporative losses resulting from dammed water. PV panels occasionally require water for cleaning, the water impact of wind turbines and ocean energy is negligible (Macknick et al., 2011).

2.3.2 Cooling systems

All wet thermal electricity generators require a cooling system. Three basic cooling technologies exist, which all have a significantly different water impact; once-through cooling, a cooling tower (also called wet cooling or recirculating cooling) and dry cooling (Kessler & Knight, 2005; Averyt et al., 2011; Macknick et al., 2011). The working principle of the three cooling systems is similar; steam that has passed through the steam turbine has to be condensed using another fluid or gas. The condensed steam can be reused as working fluid because it is circulated in a closed loop. Therefore, the water impact of thermal generators as a result of their working fluid is minimal. The cooling system accounts for virtually all water used by wet thermal electricity generators (Averyt et al., 2011).

Once-through cooling is the most basic cooling system. Once-through cooling systems withdrawal water from their environment, which can even be saline water, pass the water through condensers and discharge warmer water back to the environment. Once-through cooling systems have long been the most popular cooling systems for large scale production because of their simplicity and low costs (UCS, 2016). With once-through cooling almost no water is lost due to evaporation, but the discharge of warmer water might have a negative impact on the local ecosystem (Kessler & Knight, 2005). Cooling towers do not directly discharge water after it has passed the condensers, but circulate water multiple times through the condensers. By doing so, less water has to be withdrawn from the local environment, but more water is lost through evaporation. Nowadays, cooling towers are most popular for large scale electricity production (USC, 2016). Cooling towers are characterized by large chimneys producing vapour plumes, as can be seen in figure 6 (ATS, 2017). However, more modern cooling towers are much smaller. Finally, dry cooling systems do not use water but blow air across steam carrying pipes to cool them. Therefore, the only water requirement for generators using dry cooling is the working fluid (Averyt et al., 2011). Dry cooling systems are most modern cooling systems but implementation is still low because of high costs and lower efficiencies (USC, 2016).

Figure 6: Typical cooling tower (ATS, 2017).

3. Methodology

This section describes the methodology that is developed in this study to assess the local freshwater and carbon impact of using EVs. In section 3.1.1 the design of the methodology is visualized, including a brief description of the types of concepts and relations it includes. Sections 3.1.2 to 3.1.4 provide an elaborate definition and justification of all concepts.

3.1 Design of the methodology

The methodology developed in this study is visualized in a conceptual model in figure 7. A distinction is made between three types of concepts; input variables, intermediate results and final results.

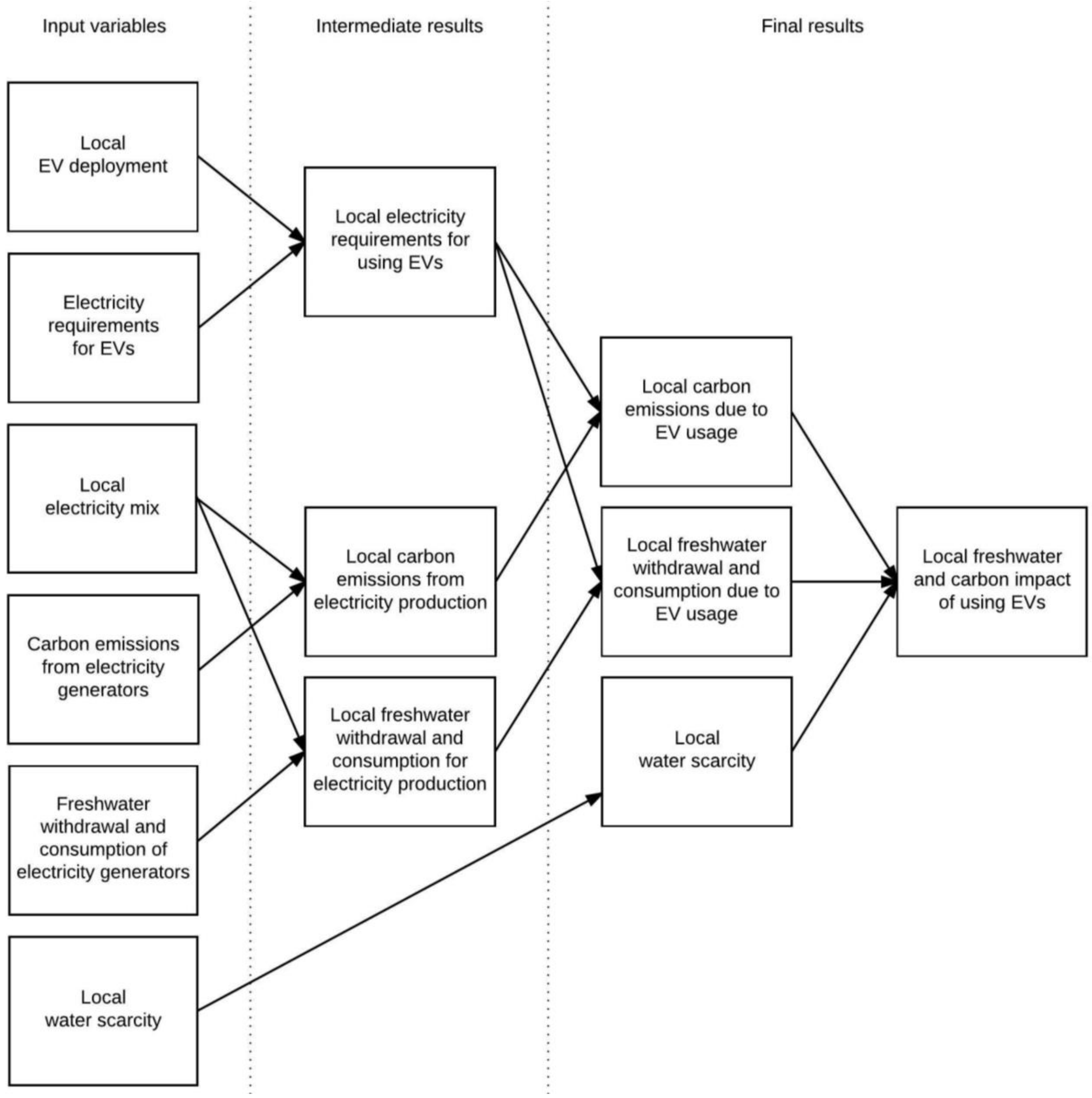


Figure 7: Conceptual model of the developed methodology.

In the conceptual model it can be seen that six input variables form the basis of the proposed methodology. The input variables are the only concepts that require external data. The intermediate results are quantitatively related to the input variables, which means that each intermediate result can be calculated directly using the data of its input variables. The intermediate results form in their turn the quantitative input for the first two final results. The third final result, the *Local water scarcity*, is the same as its input variable because the data of this input variable can be used directly in the final results. The three final results together can be used to determine the *Local freshwater and carbon impact of using EVs*.

It must be noted that in the ideal situation external data is available which can be used directly as input for the intermediate results, for example by collecting water usage and greenhouse gas emission data from all power plants in the region. However, it is not expected that all this data is available. Therefore, this paper proposes a methodology which is partly based on assumptions and therefore has less accurate final results than in the ideal situation. However, when the methodology is implemented correctly and the required data is available, still a very reliable and useful result can be achieved.

3.2 Definition of input variables

3.2.1 Local EV deployment

The concept *local EV deployment* is the starting point of the proposed methodology for assessing the local impact of using EVs. The concept describes the EV deployment in a region, expressed in the annual driving distance of EVs propelled by the electromotor. This means that data is needed on the number of EVs registered in a given region and what the average annual driving distance of these EVs is. Because the composition of the EV fleet strongly affects the actual number of kilometres propelled by the electromotor, it is important to specify the share of FEVs, E-REVs and PHEVs.

Data about number of EVs registered in the investigated region can be collected in three different ways. The first option is that the methodology is used to assess the impact of an existing EV fleet. In that case data about existing EV fleets can be collected from national data agencies, like the Dutch Central Agency for Statistics (in Dutch: Centraal Bureau voor de Statistiek (CBS)). In the second option the methodology is used to assess the impact of EV deployment targets set by (local) governments, for example, when India achieves its target of 300,000 EVs in 2020. To find these targets (national) policy documents can be consulted, or international reports like the Global EV Outlook (IEA, 2016). The third option is that the methodology is used to assess the impact of a predicted future increase in EV usage, based on local and technological developments. Such predictions give a more realistic view on the future EV deployment than policy targets, because it is always questionable if policy targets will be achieved. However, making future predictions can be difficult and time consuming because EV adoption and usage depends on multiple factors, like financial incentives given by (local) governments, the availability and reliability of charging infrastructure and consumer characteristics (Coffman, Bernstein, & Wee, 2015).

Data about the average annual driving distance of passenger vehicles in regions is often provided by national research institutes, like the Federal Highway Administration (FHWA) in the United States. It is important to use local data because the average annual driving distance can differ strongly among regions. In the American state of Texas, for example, the average annual driving distance of a passenger vehicle is over 25.000 km, while in Alaska the annual average is less than half of that (FHWA, 2016). Data about the average annual driving distance of passenger vehicles is often not specified per fuel type. However, a research of the Idaho National Laboratory (INL, 2015) showed that EV owners in the United States use their car similar to owners of conventional cars. Therefore it can be assumed that the annual mileage of EVs is the same as the regional average.

3.2.2 Electricity requirements for EVs

The concept *electricity requirements for EVs* refers to the amount of electricity that has to be produced at the source (e.g. a power plant or windmill) to drive an EV, expressed in kilowatt-hour per kilometre (kWh/km). This means that not only data is needed on the electricity consumption when driving an EV, but also about the efficiency of transmitting, distributing and charging the required electricity, as visualized in figure 8.

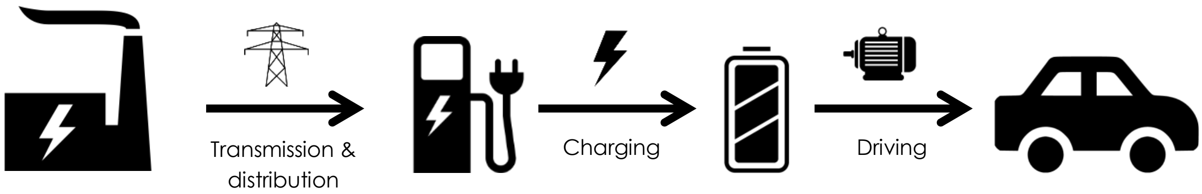


Figure 8: Steps from electricity at its source to power at the wheels that are included in the concept electricity requirements for EVs.

The most important aspect of this concept is the electricity consumption when driving an EV. This aspect is dependent on car characteristics (e.g. weight, resistance and auxiliary electrical equipment), road and driving characteristics and weather conditions (Helms, Pehnt, Lambrecht, & Liebich, 2010). Most manufacturers provide data about the electricity consumption of their EV. However, efficiencies provided by manufacturers often do not correctly represent the practical usage of cars because they are measured in ideal test situations (Helms et al., 2010). Besides that, car manufacturers often do not include data about the effect of ambient temperatures on the overall efficiency of EVs. Therefore, it is recommended to use test results of independent studies which provide standard values about the energy consumption of driving an average sized family EV, with an average driving profile, at different ambient temperatures, like the study of Yuksel & Michalek (2015).

Charging efficiencies differ per vehicle and charging system but differences are only small (Helms et al., 2010). Therefore, it is recommended to use a standard value from existing literature for the charging loss; ranging from 10% to 13% (Kintner-Meyer, Schneider, & Pratt, 2007; King & Webber, 2007; Helms et al., 2010). Transmission and distribution losses, on the other hand, differ strongly per country. In The Netherlands, for example, only 4% of the electricity output was lost during transmission and distribution in 2013, while in Haiti 54% of the electricity was lost (Worldbank, 2014). Therefore it is important to use location specific data for the transmission and distribution losses. The Worldbank (2014) provides an overview of the average losses in almost all countries.

3.2.3 Local electricity mix

The concept *Local electricity mix* refers to the technologies that are used in the investigated region to produce electricity. The concept is expressed as the contribution of each type of technology to the total electricity production in a region per season. This information is essential for calculating the carbon and water impact of local electricity production because there are large differences between the impacts of different technologies (Sathaye et al., 2011; Macknick et al., 2011; Schornagel et al., 2012; Graff Zivin, Kotchen, & Mansur, 2014). For this concept data about the fuels, generation technologies, cooling systems and water types used in the local electricity mix is required.

An important assumption for this concept is that all electricity consumed in a region is also produced in that region. This means that this concept only focuses on the electricity mix within the borders of the investigated region. It might be possible, though, that the electricity produced in a region is not the exact representation of the electricity consumed in that same region, due to electricity imports and exports. However, it is nearly impossible to trace back the origin of every single kWh. Data of Indexmundi (2016) shows that the average global electricity import is less than 3,5% of the global electricity consumption. Based on this number a fair assumption can be made that the electricity mix in a region is a good representation of the electricity consumed in that region.

The data that must be collected for this concept is important for different parts of the assessment. The types of fuel used in the local electricity mix are important for calculating the carbon emissions of the electricity mix (Edenhofer et al., 2014). Additional information about the generation technologies, cooling systems and water types that are used in the local electricity mix are necessary to calculate the water impact of the electricity mix (Macknick et al., 2011; Schornagel et al., 2012). Because so many different input data is necessary, four steps are given which describe how all required data about the local electricity mix can be collected in a structured way. Data required for the four steps is often provided by public energy authorities like the Indian Central Electricity Authority (CEA, 2016) and the California Energy Commission (CEC, 2016), or by energy companies operating the power plants.

- **Step 1:** Find an overview of all generators producing electricity within the investigated region, including their seasonal electricity production in GWh (winter = January, February, March; spring = April, May, June; summer = July, August, September; fall = October, November, December). Due to weather circumstances the seasonal electricity production per fuel can differ significantly. Hydropower stations, for example, can have significantly higher outputs in wet seasons (CEA, 2016). However, when only annual production data is available it must be assumed that the production is evenly distributed over each season.
- **Step 2:** Collect data about the input fuel per generator, based on the categorization of Moomaw et al. (2011). Moomaw et al. (2011) makes a distinction between 11 fuels which can be used for electricity production (e.g. coal, natural gas, wind and biomass). Note that some generators use a secondary fuel next to their primary fuel for part of the electricity production. In that case the share of each fuel to the total electricity production must be included. The total electricity production per fuel is sufficient to determine the carbon emissions of the total electricity mix and the water usage of non-thermal generators (solar (PV), wind, ocean and hydropower). For all thermal generators more data is necessary to determine their water usage.
- **Step 3:** Collect data about the generation technology of all thermal generators, based on the categorization made by Macknick et al. (2011), extended with combustion turbines. Macknick et al. (2011) makes a distinction between 22 generation technologies divided over the six possible input fuels of thermal generators (e.g. supercritical turbines for coal fired generators and combined cycles for natural gas fired generators). Macknick et al. (2011) leaves out combustion turbines because they do not use any water (Power Engineering, 2014). However, combustion turbines are nowadays a mature technology for oil, natural gas

and biomass fired generators so they have to be included in the categorization. Because combustion turbines, also called wet thermal generators, do not use any water, no further data is necessary to determine their water usage. For all other thermal generators, the wet thermal generators, more data is necessary to determine their water usage.

- **Step 4:** Collect for all wet thermal power plants data about the cooling system they have and the type of water they use (fresh, brackish or saline water). With this data, also for wet thermal generators the data is sufficient to determine their water usage.

When all data required for the four steps is available, an assessment with high reliability can be performed. However, based on experiences of the case studies, it can be expected that part of the data is missing or incomplete in many regions. When data is (publicly) unavailable it differs per region what part of the data is missing. Some situations of data unavailability occur more often than others but still allow for a proper implementation of the methodology. Four typical situations for data availability are described box 1, with an explanation of how to minimize the negative effect of missing data on the reliability of the results. When no data is missing, box 1 can be skipped.

Box 1: The consequences of 4 situations regarding data unavailability for the concept local electricity mix

For some wet thermal generators data about the cooling system and water type is unavailable.

This situation relates to step 4 of the data collection and can occur in every region, even in regions with very structured energy databases. In this situation the average of all wet thermal generators which do have complete data can be used for the generators with missing data. The reliability of the results depends on the share of the total electricity production of wet thermal generators for which complete data is available.

For some thermal generators data about the generation technology is unavailable.

This situation relates to step 3 of the data collection and can also occur in every region. In this situation it is not possible to separate all dry thermal generators from the wet thermal generators. Because of this, the average of all thermal generators with complete data must be used for all thermal generators with missing data. However, because dry thermal generators are in general smaller than wet thermal generators, the generators with complete data must be evenly distributed over all generator sizes. This in order to prevent that only the largest thermal generators have complete data, resulting in an overestimation of the water usage of all thermal generators, or the other way around. Therefore, the results of this situation are only reliable when the generators with available data cover a significant part of the electricity production by both large (>250 MW) and small generators (≤250 MW).

For the renewable production only data about the production per fuel is available, not per generator.

This situation relates to step 1 and 2 of the data collection and can occur in regions with only small scale renewable energy production. Because the renewable energy generators are small, their cumulative production is published instead of the production per generator. For all non-thermal renewables this is no problem, because data about their production per fuel is sufficient. However, for the thermal renewables more detailed information per generator is necessary. In this situation the total production of the thermal renewable generators gets the average of all other (non-renewable) thermal generators. The reliability of the results of this situation depends on the share of thermal renewables to the total thermal production.

For the total electricity production only data about the production per fuel is available, not per generator.

This situation also relates to step 1 and 2 of the data collection and is likely to occur in the European Union. Due to the liberalization of the electricity market no detailed production data per generator is available (TenneT, 2017; CBS, 2017d). In this situation it is impossible to determine the contribution of individual generators to the total electricity production. Therefore, the assessment can only be based on estimations about the technologies used in the electricity mix. When doing this, it is recommended to use at least the most negative scenario regarding the freshwater impact of the electricity mix. This means that, especially for cooling systems, the most water intensive systems are selected. The results of this situation will not be reliable, but can be used to get a first indication of the local freshwater and carbon impact of EV usage.

3.2.4 Carbon emissions from electricity generators

The concept *Carbon emissions from electricity generators* refers to the carbon emissions from different electricity generation technologies, expressed in tonnes carbon dioxide per gigawatt-hour (tonne CO_2/GWh). Because this methodology focuses on the local impact of using EVs, only the local carbon emissions of electricity generators are included. However, because the negative impact of carbon emissions is only visible on a global skill, time and location of the emissions is less relevant (Edenhofer et al., 2014). Therefore, it can be argued that the complete lifecycle carbon emissions of electricity generators have to be included, even the carbon that is not emitted locally. However, by far the largest share of the total lifecycle emissions of most electricity mixes can be attributed to electricity produced with fossil fuels. Besides that, fossil fuelled generators emit by far the largest share of their total lifecycle emissions on-site during the operational phase, due to the combustion of fuels (Sathaye et al., 2011; Moomaw et al., 2014; Edenhofer et al., 2014). Therefore, a fair assumption can be made that most carbon emissions are covered when focusing on the local emissions of fossil fuelled electricity generators during the operational phase.

For this concept it is assumed that data about the exact greenhouse gas emissions of all fossil fuelled electricity generators in a region is not available. Therefore, standard values about the carbon content of coal, oil and natural gas have to be used. Besides that, the efficiency of fossil fuelled generators differs strongly per country (Hussy et al., 2014). This is a result of differences among countries in the average age and quality of generators, and differences in generation technologies contributing to the total production per fuel (e.g. a larger share of supercritical coal power plants leads to a higher average efficiency of coal production in a country). Data about both the average carbon content of fuels and the average efficiency of electricity generators per fuel and per country is provided by multiple energy and research agencies.

3.2.5 Freshwater withdrawal and consumption of electricity generators

The concept *freshwater withdrawal and consumption of electricity generators* refers to the freshwater that is withdrawn and consumed during the process of generating electricity, expressed in cubic meter per gigawatt-hour (m^3/GWh). As can be seen in the definition of this concept, the focus is only on the usage of fresh water, not on the usage of brackish or saline water. Because no saline water scarcities exist, using saline water has no impact on the local water scarcity (Hoekstra et al., 2012). It is important to account for all types of fresh water that can be used by electricity generators, even waste water. Fresh waste water is still a very valuable resource because it can be used for multiple human purposes with only limited treatment (USGS, 2016b). Therefore, also the usage of wastewater can contribute the local fresh water scarcity.

Because this methodology focuses on the local impact of using EVs, also this concept only includes the on-site water usage during operation. The water intensity of constructing and dismantling electricity generators is not included because in most cases this intensity is negligible compared to the water intensities of operation (Mekonnen et al., 2015). Also the water intensity for resource extraction, which is relevant for fuel-based electricity like coal, uranium and biomass, is not included, because also this intensity is generally negligible compared to the power plants' intensities (Schornagel et al., 2012). The only exception on the latter is the production of biomass, which has large water intensity when crops are solely cultivated for the production of biomass (Schornagel et al., 2012). However, because biomass production is not location bound it is difficult to assign the impact to a certain location. Besides that, most feedstock for biomass still consists of waste generated by the forestry industry, farms or municipalities (Schornagel et al., 2012; Bracmort, 2011). Nevertheless, in regions with a large share of biomass fired generators one must be aware that the water impact of EV usage might be significantly larger when the production of biomass is included.

Also for this concept, it is assumed that data about the exact water usage of each individual power plant in the investigated region is not available. Therefore, standard values have to be used about the water withdrawal and consumption of electricity generators per input fuel, generation technology and cooling technology. It is important to keep in mind that local differences might occur, but in general water usage related to electricity and heat generation in specific plants will stretch across the globe (Mekonnen et al., 2015). Therefore, it will be sufficient to use global averages for the water intensity of electricity generators. Multiple studies exist on the water impact of electricity generation, but it is recommended to use the study of Macknick et al. (2011) for this assessment. Macknick et al. (2011) provides data on the water impact of multiple types of electricity generators for the operational phase only.

3.2.6 Local water scarcity

The concept *local water scarcity* refers to the water stress in a region, expressed in a dimensionless number comparing the water consumption in a region over the water availability, also referred to as the CTA index. The CTA index is used for this concept over other water scarcity indices because it is more convenient to focus water scarcity on water consumption instead of withdrawal (Hoekstra et al., 2012). Water withdrawals alone do not contribute to water scarcity, because water becomes available for reuse when it is discharged to the same watershed. Only when water is consumed and is not available to the local environment anymore, it contributes to water scarcity. Activities requiring large amount of water withdrawals can only be negatively affected by existing water scarcity, because the required water may not be available anymore.

This concept focuses on blue water scarcity only, excluding green and grey water scarcity. The power sector does not rely on the direct consumption of rainwater. All water required by the power sector is extracted from the environment in a controlled way, for example by the extraction of surface or groundwater (Macknick et al., 2011). This means that the power sector does not make use of green water. Besides that, it is expected that a power plants' discharge water meets agreed water quality standards, excluding the need for grey water. Because water scarcity can have large seasonal differences it is essential to have seasonal data about the blue water scarcity in the investigated region. Besides that, not only data about the resulting water scarcity must be collected, but also about the absolute values of blue water availability and blue water consumption. Existing studies regarding blue water scarcity can be used to collect the required data.

3.3 Definition of intermediate results

All intermediate results are quantitatively related to their input variables. Therefore, formulas suffice as definition of the intermediate results.

Local electricity requirements for using EVs

$$\mathbf{E_{r,tot}} = \frac{\mathbf{n_{EV} * d_{EV,av} * E_{r,av}}}{\mathbf{\eta_{ch} * \eta_{dt}}}$$

$E_{r,tot}$ = Total local electricity requirements for using EVs (GWh/y)
n_{EV} = Number of EVs
$d_{EV,av}$ = Average driving distance per EV (km/y)
$E_{r,tot}$ = Average electricity requirements of EVs (GWh/km)
η_{ch} = Charging efficiency (= 1 − charging loss)
η_{dt} = Distribution and transmission efficiency (= 1 − distribution and transmission loss)

Local carbon emissions from electricity production

$$\mathbf{Em_{CO_2,av}} = \frac{\sum \mathbf{E_{p,f}} * \frac{\mathbf{C_f}}{\mathbf{\eta_{p,f}}}}{\mathbf{E_{p,tot}}}$$

$Em_{CO_2,av}$ = Average local carbon emissions from electricity production (tonne CO_2/GWh)
$E_{p,f}$ = Electricity production of fuel f (GWh/y)
C_f = Carbon emission factor of fuel f (tonne CO_2/GWh)
$\eta_{p,f}$ = Production efficiency of fuel f
$E_{p,tot}$ = Total local electricity production (GWh/y)

Local freshwater withdrawal and consumption for electricity production

$$\mathbf{F_{w,av}} = \frac{\sum \mathbf{E_{p,g} * W_g}}{\mathbf{E_{p,tot}}}$$

F_w = Average local freshwater withdrawal for electricity production (m^3/GWh)
$E_{p,g}$ = Electricity production of generator g (GWh/y)
W_g = Freshwater withdrawal factor of generator g (m^3/GWh)

$$\mathbf{F_{c,av}} = \frac{\sum \mathbf{E_{p,g} * C_g}}{\mathbf{E_{p,tot}}}$$

F_c = Average local freshwater consumption for electricity production (m^3/GWh)
C_g = Freshwater consumption factor of generator g (m^3/GWh)

3.4 Definition of final results

The concepts *local carbon emissions due to EV usage* and *local freshwater withdrawal and consumption due to EV usage* are quantitatively related to their intermediate results. Therefore, also for these concepts formulas suffice as definition. For the concept local water scarcity the exact same input data can be used as its input variable, so no further definition is required.

Local carbon emissions due to EV usage

$$\mathbf{Em_{CO_2,tot} = E_{r,tot} * Em_{CO_2,av}}$$

$\mathrm{Em_{CO_2,tot}}$ = Total local carbon emissions due to EV usage (tonne CO_2/y)

Local freshwater withdrawal and consumption due to EV usage

$$\mathbf{F_{w,tot} = E_{r,tot} * F_{w,av}}$$

$\mathrm{F_{w,tot}}$ = Total local freshwater withdrawal due to EV usage (m^3/y)

$$\mathbf{F_{c,tot} = E_{r,tot} * F_{c,av}}$$

$\mathrm{F_{c,tot}}$ = Total local freshwater consumption due to EV usage (m^3/y)

Local water scarcity

Exact same data can be used as the input variable.

Local freshwater and carbon impact of using EVs

The final concept is the interpretation of the results, which must be done by comparing the final results. Two main comparisons are important to make. First, it is important to determine the freshwater withdrawals due to EV usage as share of the total natural blue water runoff in a region. By doing so, it can be seen if the required amount of freshwater for EV usage is naturally available and what share has to be withdrawn. Secondly, it is important to determine the freshwater consumption due to EV usage as share of the existing blue water footprint. By doing so, it can be seen what the relative contribution of EV usage is to the local water scarcity, and if EV usage will result in water scarcities reaching over critical levels of 20%, 30% or 40%. Besides that, it is interesting to look at the carbon intensity of EV usage compared to conventional gasoline and diesel cars, and what the relation is between the carbon and freshwater impact of the electricity mix.

4. Data collection

In the second part of this study the developed methodology is applied to three regions. A selection is made of three regions with ambitious EV deployment targets and distinguishing characteristics regarding water availability or electricity production; California (United States), Rajasthan (India) and The Netherlands. The case studies will assess the local carbon and freshwater impact of the targeted EV fleet in 2020, and the situation in which 50% of the existing passenger car fleet is electric. By doing so, the impact of a realistic scenario in the near future can be investigated, together with the impact of a hypothetical future scenario when EVs become the new standard for passenger vehicles. In this chapter the collected data for each of the six input variables for the case studies is presented.

4.1 Local EV deployment

Table 2 presents the collected data for the concept *local EV deployment*. For California only data was available about the EV deployment target for 2025, not for 2020. To estimate the EV deployment in 2020 it is assumed that the EV fleet in California will have a constant rate of increase from 2015 till the target of 1,5 million EVs in 2025 (ZEV Working Group, 2016). To reach the target an annual increase rate of 19% is required, which will lead to an EV deployment of 650.000 vehicles in 2020. For India only data was available about national EV deployment. In 2015 there were 6.000 EVs on the Indian roadways and the target is to have 300.000 EVs in 2020 (IEA, 2016). To estimate the values for Rajasthan the national values are corrected for the population; Rajasthan houses 5,6% of the Indian population (IndiaOnline, 2016a; IndiaOnline 2016b). Based on this ratio the target for Rajasthan is to have an EV deployment of 17.000 vehicles in 2020. The deployment targets did not specify the share of FEVs, E-REVs and PHEVs. Therefore, it is assumed that the targeted EV fleet in the investigated regions will have the same composition as the global average in 2015: 60% FEVs, 40% PHEVs and a negligible number of E-REVs (IEA, 2016). Besides that, it is assumed that PHEV owners will use their electromotor similar to PHEV owners in California, who use their electromotor for 50% of the total driving distance (Axsen & Kurani, 2010).

Table 2: Input data for the concept 'Local EV deployment'

Variable	California		Rajasthan		The Netherlands	
Total passenger car deployment (cars)	27.697.923	(1)	9.722.904	(5)	8.100.864	(7)
2015 EV deployment (EVs)	265.195	(2)	336	Est.	98.930	(8)
2020 EV deployment target (EVs)	650.000	Est.	17.000	Est.	300.000	(3)
Average driving distance (km/EV/year)	17.870	(1)	12.000	(6)	12.267	(7,9)
Share of FEVs	60%	(3)	60%	(3)	60%	(3)
Share of PHEVs	40%	(3)	40%	(3)	40%	(3)
Electromotor usage by PHEVs	50%	(4)	50%	(4)	50%	(4)

References: (1) FHWA (2016); (2) PEV Collaborative (2016); (3) assumption based on IEA (2016); (4) assumption based on Axsen & Kurani (2010); (5) Ministry of Road Transport and Highways (2011); (6) Goel et al. (2016); (7) CBS (2017a); (8) RVO (2017); (9) CBS (2017b).

4.2 Electricity requirements for EVs

The main data for the concept *electricity requirements for EVs* is the electricity consumption while driving an EV. Because the ambient temperature strongly influences the efficiency of EVs, data at different ambient temperatures is collected. For this study standard values provided by Yuksel & Michalek (2015) are used, because they provide independent test results about the energy consumption of driving an average sized family EV, with an average driving profile. The values are presented in table 3.

Table 3: Electricity consumption while driving an EV at different ambient temperatures

Temperature (°C)	Electricity consumption while driving an EV (kWh/100km)
-15	24,0
-10	23,5
-5	22,5
0	21,5
5	20,0
10	18,5
15	17,5
20	17,0
25	18,0
30	19,5
35	23,5
40	26,5

Reference: Yuksel & Michalek (2015).

In table 4 the average seasonal and annual ambient temperature in the three investigated regions is presented. The average temperatures are rounded to the nearest 5-degree temperature of table 4 to find the corresponding electricity consumption. Average distribution, transmission and charging losses are displayed in table 5. For the charging loss no indication was found that there are significant differences among different countries. Therefore, standard values are used which, however, vary slightly among existing literature. For this study the average of the charging losses presented by Kintner-Meyer et al. (2007), King & Webber (2007) and Helms et al. (2010) is used.

Table 4: Average seasonal and yearly ambient temperature in the investigated regions

Seasonal temperature	California (°C)	Rajasthan (°C)	The Netherlands (°C)
Winter	9	18	3
Spring	15	30	10
Summer	23	31	17
Fall	17	26	11
Annual	16	26	10

References: California: US Climate Data (2017); Rajasthan: World Weather Online (2017); The Netherlands: Weerstatistieken (2017).

Table 5: Average distribution, transmission and charging loss in the investigated regions

Electricity loss	California	Rajasthan	The Netherlands
Distribution and transmission	6%	18%	4%
Charging	12%	12%	12%

References: distribution and transmission losses: Worldbank (2014); charging losses: average from Kintner-Meyer et al. (2007), King & Webber (2007)and (Helms et al., 2010).

4.3 Local electricity mix

For the concept 'Local electricity mix' data about the electricity mix in the investigated regions is collected. In table 6 an overview of the annual electricity production per input fuel in the three investigated regions is displayed for the most recent year data was available.

Table 6: Electricity mix in the investigated regions in annual production per fuel

Input fuel	California (GWh in 2015)	Share (%)	Rajasthan (GWh in 2016)	Share (%)	Netherlands (GWh in 2015)	Share (%)
Coal	12.375	6%	42.743	70%	38.864	35%
Natural gas	126.503	56%	2.218	4%	46.163	42%
Oil	54	0%			77	0%
Nuclear energy	18.525	8%	7.380	12%	4.078	4%
Biomass	6.362	3%	272	0%	4.967	5%
Wind	12.835	6%	5.328	9%	7.489	7%
Water	17.642	8%	988	2%	93	0%
Solar energy (PV)	15.212	7%	2.117	3%	1.108	1%
Solar energy (CSP)	2.446	1%				
Geothermal energy	12.456	6%				
Other	189	0%			7.163	7%
Total	**224.599**		**61.046**		**110.002**	

References: California: California Energy Commission (CEC, 2016); Rajasthan: Indian Central Electricity Authority (CEA, 2016); The Netherlands: Dutch Central Authority of Statistics (CBS, 2017c).

For this concept more detailed data about the electricity mix is required than only the annual electricity production per fuel, like data about the generation technology and cooling system per generator. However, the availability of more detailed data differed strongly per region. For California comprehensive data about the electricity mix was available in the California Energy Almanac, published by the California Energy Commission (CEC, 2016). The Almanac provides data about the annual production, input fuel and generation technology of each individual electricity generator in the region in 2015. Besides that, for 73% of the wet thermal generators data about the cooling technology and water type was included. For this study it is assumed that this level of data availability is sufficient to draw reliable conclusions. Because only annual and no seasonal production data was available for 2015, it is assumed that the production was constant throughout the year. An overview of the electricity mix in California in annual production per input fuel, generation technology, cooling system and water type can be found in Appendix A.

For Rajasthan, data is published about the monthly electricity production of all fossil fuelled and nuclear generators in the region by the Indian Central Electricity Authority, which is part of the Indian Ministry of Power (CEA, 2016). For all renewables, however, only data about the combined production per fuel is published, not per generator. Therefore, the assumption was made that all thermal renewable generators have the same freshwater impact as the average of all other thermal generators in Rajasthan. Besides that, it is assumed that all solar energy consists of PV panels and no CSP generators are installed. For all fossil fuel and nuclear generators data about the generation technology, cooling technology and water type was collected using grey literature, like documents provided by energy companies operating power plants. In the end, complete data was available of 95% of all thermal generators. Therefore, it is assumed that the level of data availability in Rajasthan is sufficient to draw reliable conclusions. Because the production data was available per month in 2016, the production of the months per season are combined to get the production per season. Only for renewables the production of the first three months in 2016 was missing. It is assumed that in these three months renewables had the same production as the average of the production in December 2015 and April 2016. Appendix B provides an overview of the electricity mix in Rajasthan in seasonal production per power plant, including their primary fuel, generation technology, cooling system and water type.

For the Netherlands limited data was available. Since the liberalization of the electricity market in the European Union most production and technical data about individual power plants has become commercially sensitive (TenneT, 2017; CBS, 2017d). Besides that, because water scarcity is not an important public debate in the Netherlands, energy companies do not often mention information about the cooling systems in the general description of their power plants. Therefore, the only publicly available data about the electricity mix in the Netherlands is data about the annual production per fuel, published by the Dutch Central Authority of Statistics (CBS, 2017c). With only this data available, no reliable conclusions can be drawn about the water impact of the electricity mix. Therefore, two scenarios for have been outlined; a negative scenario in which the cooling systems in the Dutch electricity mix are very old-fashioned, and positive scenario in which the cooling systems are very modern. The characteristics of the two scenarios are displayed in table 7.

In both scenarios it is assumed that all solar power in the Netherlands consists of PV panels and no CSP generators are installed. Besides that, it is assumed that all oil fuelled generators are combustion generators. With these assumptions, only for natural gas, coal, biomass and nuclear fuelled generators more information is required to determine their water usage. In both the negative and the positive scenario these generators have the average water impact of all generation technologies using the same fuel as presented by Macknick et al. (2011), and only freshwater is used. The cooling systems, however, differ in both scenarios. In the negative scenario the oldest generators in the Netherlands, which are on average coal and nuclear generators, have the most old-fashioned cooling system; once-through cooling. The more modern generators, which are on average the natural gas and biomass fuelled generators, are equipped with cooling towers. In the positive scenario the older generators are equipped with cooling towers and the more modern generators with modern dry cooling systems.

Table 7: Two scenarios for the technical characteristics of the electricity mix in the Netherlands

Fuel	Negative scenario			Positive scenario		
	Generation technology	Cooling system	Water type	Generation technology	Cooling system	Water type
Natural gas	Average	Tower	Fresh	Average	Dry	Fresh
Coal	Average	Once-through	Fresh	Average	Tower	Fresh
Biomass	Average	Tower	Fresh	Average	Dry	Fresh
Nuclear	Average	Once-through	Fresh	Average	Tower	Fresh

With these scenarios no conclusions about the specific case of the Netherlands can be drawn, because it is not known which of the scenarios is more in line with the actual situation, but the scenarios can be used to investigate the water impact of two extreme situations for the electricity mix. Appendix C provides a detailed overview of the Dutch electricity mix per fuel, generation technology, cooling system and water type for both scenarios.

4.4 Carbon emissions from electricity generators

To calculate the carbon emissions from electricity generators data is collected about the standard carbon dioxide emission factors of fossil fuels, which are displayed in table 8, and the average efficiencies of fossil fuelled generators in the investigated regions, which are displayed in table 9. Because data about the electricity mixes in the investigated regions does not specify between types of coal and oil that are used for electricity production, the average emission factors of different types of coal and oil are used in this study. The emissions factor of coal is the average of the emission factors of anthracite, bituminous coal, subbituminous coal and lignite. The emission factor of oil is the average of gasoline, diesel fuel and heating oil (EIA, 2016b).

Table 8: Average carbon dioxide emission factors of fossil fuels

Fuel type	Carbon emissions (tonnes CO_2/GWh)
Coal	334
Oil	246
Natural gas	181

Reference: U.S. Energy Information Administration (EIA, 2016b).

Table 9: Average efficiency of fossil fuelled generators in the investigated regions

Input fuel	California	Rajasthan	The Netherlands
Coal	35,8%	27,1%	40,4%
Natural gas	49,2%	50,6%	47,2%
Oil	39,4%	20,0%	35,9%

Reference: Hussy et al. (2014)

4.5 Freshwater withdrawal and consumption of electricity generators

This study makes use of standard water withdrawal and consumption factors of electricity generators presented by Macknick et al. (2011). This data is used only includes the water consumption during the operational phase and it combines water usage data of multiple existing studies, making the results more reliable. Table 10 displays the water usage factors of the generation technologies that are present in the electricity mix of one or more of the investigated regions.

Table 10: Average water usage factors for selected electricity generation technologies

Fuel type	Generation technology	Cooling system	Water withdrawal (m^3/GWh)	Water consumption (m^3/GWh)
Non thermal generators				
Solar (PV)	Photovoltaic cells		98	98
Wind	Wind turbine		0	0
Hydropower	Hydroelectric generator		17.000	17.000
Wet thermal generators				
Coal	Generic	Tower	3.804	2.600
	Subcritical	Tower	2.010	1.782
		Once-through	102.539	427
	Supercritical	Tower	2.305	1.866
Natural Gas	Combined cycle	Tower	957	749
		Once-through	43.077	378
		Dry	8	8
	Steam	Tower	4.553	3.126
		Once-through	132.489	908
Nuclear energy	Generic	Tower	4.167	2.543
		Once-through	167.883	1.018
Solar (CSP)	Trough	Tower	3.274	3.274
Biogas	Biogas	Tower	889	889
		Dry	132	132
Geothermal energy	Dry steam	Tower	6.798	6.798
	Binary	Tower	13.627	13.627

Reference: Macknick et al. (2011).

4.6 Local water scarcity

For this study the water scarcity index of Hoekstra et al. (2012) is used to determine the blue water scarcity in the investigated regions. In the study of Hoekstra et al. (2012) the water scarcity in 405 of the largest river basins in the world is determined by comparing the blue water footprint (consumption) in a river basin with the natural runoff, also called the consumption-to-availability (CTA) index. The study of Hoekstra et al. (2012) is used because it bases water scarcity on water consumption rather than water withdrawals, and provides data on monthly basis rather than annual basis. Besides that, a data set is included with the required data of all 405 river basins. However, a limitation of the study is that not all global land area is covered by the 405 basins; the basins cover 66% of the global land area (excluding Antarctica) and represent 65% of the global population in 2000 Hoekstra et al. (2012). Also the land areas of California, Rajasthan and the Netherlands are not completely covered by the 405 river basins, which can be seen in figure 7, 8 and 9. California is partly covered by seven river basins, Rajasthan by three and the Netherlands by two.

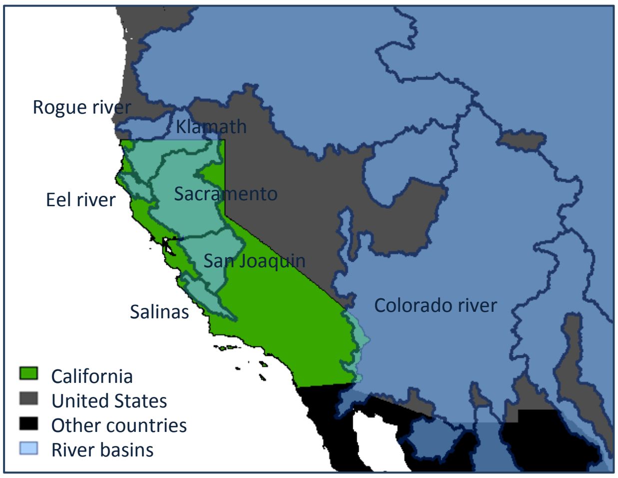
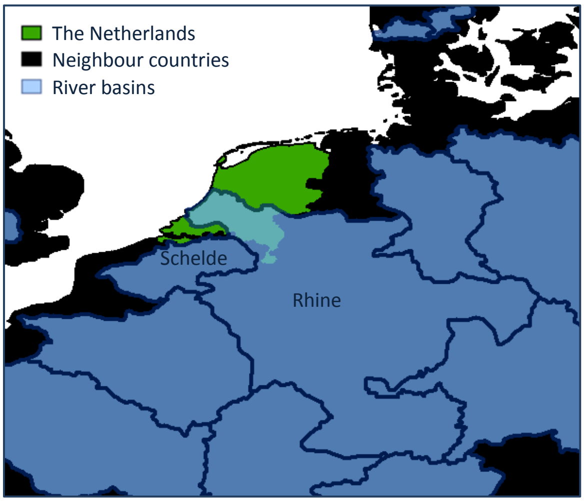


Figure 7: River basins covering California (Hoekstra et al., 2012)



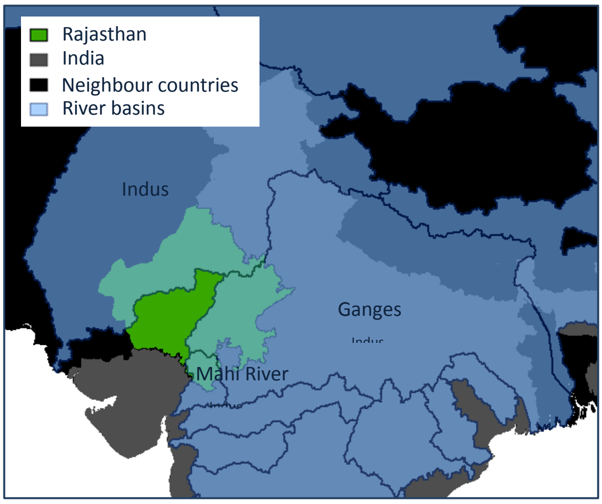


Figure 8 & 9: River basins covering the Netherlands and Rajasthan (Hoekstra et al., 2012)

For this study, the data of all river basins covering part of a region is used to approximate the water characteristics of the total region. For this approximation two important assumptions are made;

1) The average natural runoff per square kilometre outside the river basins is half the average natural runoff per square kilometre inside the river basins.
2) The average footprint per square kilometre outside the river basins is half the average footprint per square kilometre inside the river basins.

The first assumption is based on the expectation that there are more water basins in the region than only the ones investigated by Hoekstra et al. (2012). Therefore, there will be more natural blue water runoff in the region than only from the investigated river basins. It can be expected, though, that not all land area is covered by basins. Therefore, the assumption is made that the natural runoff outside the river basins is half the natural runoff inside the river basins. The second assumption is based on the expectation that water intensive human activities (e.g. agriculture and intensive industry) are concentrated within water basins.

For both assumptions it is important that river basins that are also located partly outside the investigated region are not fully included in the approximation. Therefore, the natural runoff and footprint of river basins are corrected for the share of the basins' land area that is located within the investigated region. For example; if 40% of a river basins' land area is located within an investigated region, then it is assumed that 40% of the total natural runoff and footprint of that basin can be attributed to the investigated region. With these assumptions, the resulting water scarcities show great similarities with the water scarcities provided by A. Hoekstra (2016), which presents water scarcities on a more detailed level per region. However, because A. Hoekstra (2016) only presents the resulting water scarcities and does not include data about the underlying natural runoff and footprint per region, the data was not sufficient to be used directly as input for this study. The resulting blue water characteristics for the three investigated regions are displayed in table 11. Appendix D provides detailed data of all basins covering the investigated regions.

Table 11: Blue water characteristics in the investigated regions

Season	Natural runoff (Mm^3)	Footprint (Mm^3)	Scarcity
California			
Winter	52.952	348	1%
Spring	33.407	7.846	23%
Summer	16.479	15.249	93%
Fall	8.232	1.479	18%
Annual	111.070	24.923	22%
Rajasthan			
Winter	13.277	10.037	76%
Spring	14.754	7.272	49%
Summer	55.873	6.610	12%
Fall	18.453	6.634	36%
Annual	102.356	30.553	30%
The Netherlands			
Winter	3.807	48	1%
Spring	3.113	53	2%
Summer	1.701	62	4%
Fall	2.555	49	2%
Annual	11.175	212	2%

Reference: Hoekstra et al. (2012).

5. Results

5.1 California

The local electricity requirements for future EV usage in California are displayed in table 12. Although the 2020 EV fleet will represent only 2,3% of the total passenger car fleet in California, it can be seen that electricity requirements for the fleet are already quite significant; total electricity production has to increase by almost 1% already to provide all EVs with the required electricity. With 50% EV deployment the total electricity production has to increase by nearly 20%. Small seasonal differences are the result of colder ambient temperatures in the winter and warmer ambient temperatures in the summer, which decrease the efficiency of EVs compared to an optimal temperature of 20°C.

Table 12: Local electricity requirements for future EV usage in California

Season	2,3% EV deployment (2020 target)		50% EV deployment	
	Local electricity requirements for EV usage (GWh)	Increase of total electricity production	Local electricity requirements for EV usage (GWh)	Increase of total electricity production
Winter	510	0,91%	10.871	19,36%
Spring	483	0,86%	10.283	18,31%
Summer	496	0,88%	10.577	18,84%
Fall	483	0,86%	10.283	18,31%
Annual	1.972	0,88%	42.015	18,71%

Table 13: Characteristics of the electricity mix in California

Season	Local CO_2 emissions (t/GWh)	Local freshwater withdrawal (m^3/GWh)	Local freshwater consumption (m^3/GWh)
Winter	259	2.513	2.118
Spring	259	2.513	2.118
Summer	259	2.513	2.118
Fall	259	2.513	2.118
Annual	259	2.513	2.118

The characteristics of the electricity mix in California, displayed in table 13, show that the intensity of the electricity mix is low in terms of CO_2 emissions and freshwater withdrawal. In terms of freshwater consumption the intensity is relatively high. Low carbon intensity is a result of a large share of renewables (30% of total production) and a large share of natural gas fired generators (80% of fossil fuel production). Besides that, the efficiency of fossil fuelled generators in California is high. Low freshwater withdrawals per GWh are the result of a significant contribution of combustion generators (8% of total production), PV panels (7%) and wind turbines (6%), which have no or limited water requirements. Besides that, there is a large share of thermal generators using saline water (26% of wet thermal production) and almost no contribution of thermal generators with once-through cooling using fresh water (0,4% of wet thermal production). The low carbon intensity of the electricity mix leads to an average CO_2 emission of EVs in California of 44 g/km, which is clearly lower than the average intensity of 130 g/km of newly sold cars in Europe in 2015 (Transport & Environment, 2016). The fresh water consumption per GWh, on the other hand, is relatively high as a result of a significant contribution of hydroelectric generators (8% of total production) and geothermal generators (6%), which consume by far most water of all generators. The combined water consumption of hydroelectric and geothermal generators alone represents 72% of the total fresh water consumption of the electricity mix in California. Besides that, there is a large contribution of cooling towers (70% of wet thermal production), which consume more water than once-through cooling systems.

Table 14: Local impact of future EV usage in California

Season	2,3% EV deployment (2020 target)			50% EV deployment		
	CO_2 emissions (kt)	Blue water withdrawal (Mm^3)	Blue water consumption (Mm^3)	CO_2 emissions (kt)	Blue water withdrawal (Mm^3)	Blue water consumption (Mm^3)
Winter	132	1,28	1,08	2.815	27,31	23,02
Spring	125	1,21	1,02	2.662	25,84	21,78
Summer	129	1,25	1,05	2.738	26,58	22,40
Fall	125	1,21	1,02	2.662	25,84	21,78
Annual	511	4,95	4,18	10.878	105,56	88,98

The characteristics of the electricity mix are combined with the electricity requirements for future EV usage to find the local impact of future EV usage in California, which is displayed in table 14. To determine the effect of the resulting fresh water impact on the water system in California, the impacts have to be compared with the existing blue water characteristics. This comparison is displayed in table 15. Both the withdrawal as share of the natural runoff and the consumption as share of the current footprint are displayed. Besides that, it is displayed what the contribution of the water consumption will be to more water scarcity in California.

Table 15: Blue water impact of future EV usage relative to blue water characteristics in California

Season	2,3% EV deployment (2020 target)				50% EV deployment			
	Withdra. as share of natural runoff	Consum. as share of current footprint	Current water scarcity	Increase of water scarcity (%-point)	Withdra. as share of natural runoff	Consum. as share of current footprint	Current water scarcity	Increase of water scarcity (%-point)
Winter	0,002%	0,31%	1%	0,002%	0,05%	6,62%	1%	0,04%
Spring	0,004%	0,01%	23%	0,003%	0,08%	0,28%	23%	0,07%
Summer	0,008%	0,01%	93%	0,006%	0,16%	0,15%	93%	0,14%
Fall	0,015%	0,07%	18%	0,012%	0,31%	1,47%	18%	0,26%
Annual	0,004%	0,02%	22%	0,004%	0,10%	0,36%	22%	0,08%

In table 15 in can be seen that the blue water withdrawals for EV usage as share of the natural runoff are larger in the summer than in winter. This is a result of a low natural runoff in the summer months compared to the winter months; up to 6 times smaller. On the other hand, blue water consumption for EV usage as share of the current water footprint is largest in the winter months. This is the result of a current water footprint which is over 40 times smaller in winter than in summer. These counteracting cycles of natural runoff and footprint are the cause of the existing water scarcity in California. However, the projected future EV usage in 2020 increases the shares of both the withdrawal and consumption with less than 0,5%, resulting in only a limited increases in water scarcity. With 50% EV deployment the shares become over 20 times larger, but remain small compared to the existing scarcity.

The existing water scarcity in California, however, is very high. The CTA index reaches well over 90% in summer, while existing literature defines actual water scarcity already with a CTA index over 20%

and severe water scarcity with an index over 40%. In September water scarcity reaches even over 100%, which means that the total blue water footprint is more than the total natural runoff (see Appendix D). This is possible by importing water from other regions, desalinating ocean water or draining non-replenishable aquifers. These activities, however, are very expensive, unsustainable and might lead to even more water scarcity in the near future. Therefore, any extra demand of freshwater in the summer months in California might be undesired.

5.2 Rajasthan

Table 16 displays the local electricity requirements for future EV usage in Rajasthan. EV usage in India is still in an early stage of development. Therefore, the targeted number of EVs in Rajasthan for 2020 is only 0,2% of the total passenger car fleet. The electricity requirements for using EVs in 2020 are around 10 GWh per month, which is an increase of less than 0,1% of the total electricity production in Rajasthan. Electricity requirements become much more relevant if 50% of the passenger car fleet would be electric. In this case total electricity production has to increase by almost 20%. Warm summers in Rajasthan, making EVs less efficient, result in up to 15% more electricity requirements for EV usage in the summer months compared to the winter months.

Table 16: Local electricity requirements for future EV usage in Rajasthan

Season	0,2% EV deployment (2020 target)		50% EV deployment	
	Local electricity requirements for EV usage (GWh)	Increase of total electricity production	Local electricity requirements for EV usage (GWh)	Increase of total electricity production
Winter	9	0,06%	2.621	18,04%
Spring	11	0,08%	3.007	21,56%
Summer	11	0,08%	3.007	21,96%
Fall	10	0,07%	2.776	18,97%
Annual	40	0,07%	11.411	18,69%

Table 17: Characteristics of the electricity mix in Rajasthan

Season	Local CO_2 emissions (t/GWh)	Local freshwater withdrawal (m^3/GWh)	Local freshwater consumption (m^3/GWh)
Winter	912	16.449	1.894
Spring	869	15.189	1.426
Summer	785	13.136	1.663
Fall	931	20.126	1.874
Annual	877	16.255	1.711

The electricity mix in Rajasthan is characterized by a few large coal power plants producing almost all electricity in the region. Where the largest power plant in California produced only 4% of the total production, in Rajasthan more than 70% of the total production is provided by only 6 power plants. Because of the large contribution of coal fired power plants and the low efficiency of coal plants in India, the local carbon intensity of the electricity mix in Rajasthan is high, which can be seen in table 17. The high carbon intensity of the electricity mix leads to an average CO_2 emission of EVs in Rajasthan of 171 g/km, which is even higher than the average intensity of newly sold cars in Europe. Also the freshwater withdrawals per GWh in Rajasthan are high. This can be attributed almost entirely to only one power plant; the Kota Super Thermal (KST) power plant. This coal fired power plants is the second largest plant in Rajasthan, providing over 13% of the total production, and is equipped with a once-through cooling system using fresh water. Because of this cooling system the power plants withdraws 84% of the total freshwater withdrawals for electricity production in Rajasthan. Therefore, also seasonal variations in freshwater withdrawal can only be attributed to variations in the load factor of the KST power plant. In the summer months, when electricity demand is significantly lower, production of the KST power plant is scaled back so freshwater withdrawals per GWh are up to 35% lower. The local freshwater consumption per GWh is slightly lower compared to the electricity mix in California. This is a result of a low contribution of hydroelectric generators (1,6% of total production) and no contribution of geothermal generators. Although the contribution of hydroelectric generation is only small, it is still the main attributor of seasonal variations in water consumption per GWh. In fall, just after the monsoon at the end of the summer, hydroelectric production is at its peak, while in spring the production is almost entirely stopped. As a result of this blue water consumption per GWh is almost 25% lower in spring than in fall. Table 18 displays the resulting local impact of future EV usage in Rajasthan.

Table 18: Local impact of future EV usage in Rajasthan

Season	0,2% EV deployment (2020 target)			50% EV deployment		
	CO_2 emissions (kt)	Blue water withdrawal (Mm^3)	Blue water consumption (Mm^3)	CO_2 emissions (kt)	Blue water withdrawal (Mm^3)	Blue water consumption (Mm^3)
Winter	8	0,15	0,02	2.391	43,11	4,96
Spring	9	0,16	0,01	2.614	45,67	4,29
Summer	8	0,14	0,02	2.361	39,50	5,00
Fall	9	0,20	0,02	2.584	55,86	5,20
Annual	35	0,65	0,07	10.004	185,48	19,52

Table 19: Blue water impact of future EV usage relative to blue water characteristics in Rajasthan

Season	0,2% EV deployment (2020 target)				50% EV deployment			
	Withdra. as share of natural runoff	Consum. as share of current footprint	Current water scarcity	Increase of water scarcity (%-point)	Withdra. as share of natural runoff	Consum. as share of current footprint	Current water scarcity	Increase of water scarcity (%-point)
Winter	0,0011%	0,0002%	76%	0,00013%	0,32%	0,05%	76%	0,04%
Spring	0,0011%	0,0002%	49%	0,00010%	0,31%	0,06%	49%	0,03%
Summer	0,0002%	0,0003%	12%	0,00003%	0,07%	0,08%	12%	0,01%
Fall	0,0011%	0,0003%	36%	0,00010%	0,30%	0,08%	36%	0,03%
Annual	0,0006%	0,0002%	30%	0,00007%	0,18%	0,06%	30%	0,02%

The comparison between the impact of future EV usage and the current blue water characteristics in Rajasthan is displayed in table 19. Also in Rajasthan counteracting cycles of natural blue water runoff and existing blue water footprint can be observed. In summer the natural runoff is highest, in winter the existing footprint is highest. Therefore, water withdrawals for EV usage as share of the natural runoff is lowest in summer and water consumption as share of the current footprint is lowest in winter. Because of the low EV deployment target for 2020, though, the share of both the withdrawal and the consumption is minimal. With 50% EV deployment the shares become clearly larger, but remain small compared to the existing water characteristics. However, also in Rajasthan the water scarcity is above 100% in individual months (see Appendix D), meaning that even small additions in water withdrawal or water demand might be undesired.

5.3 The Netherlands

The electricity requirements for future EV usage in the Netherlands are displayed in table 20. The 2020 target represents 3,7% of the total passenger car fleet in the Netherlands, which is the largest share of the three investigated regions. With 50% EV deployment the relative increase in electricity production is much smaller compared to the other regions. Compared to California this is the result of lower passenger car deployment per capita and lower average annual driving distance per vehicle in the Netherlands. This leads to less electricity requirements for EV usage per capita. Compared to Rajasthan the relative increase in electricity production is smaller as a result of higher current electricity consumption per person in the Netherlands. This leads to a lower relative contribution of EVs to the electricity consumption per person.

Table 20: Local electricity requirements for future EV usage in the Netherlands

Season	3,7% EV deployment (2020 target)		50% EV deployment	
	Local electricity requirements for EV usage (GWh)	Increase of total electricity production	Local electricity requirements for EV usage (GWh)	Increase of total electricity production
Winter	171	0,62%	2.315	8,42%
Spring	159	0,58%	2.141	7,79%
Summer	150	0,55%	2.026	7,37%
Fall	159	0,58%	2.141	7,79%
Annual	639	0,58%	8.623	7,84%

Table 21: Characteristics of the electricity mix in the Netherlands

Season	Local CO_2 emissions (t/GWh)	Local freshwater withdrawal (m^3/GWh)	Local freshwater consumption (m^3/GWh)
Negative scenario			
Winter	488	49.199	1.151
Spring	488	49.199	1.151
Summer	488	49.199	1.151
Fall	488	49.199	1.151
Annual	488	49.199	1.151
Positive scenario			
Winter	488	1.327	1.021
Spring	488	1.327	1.021
Summer	488	1.327	1.021
Fall	488	1.327	1.021
Annual	488	1.327	1.021

Table 21 shows the water and carbon characteristics of the electricity mix in the Netherlands. The carbon intensity is based on the actual situation and is in between the intensities of the electricity mix in California and Rajasthan. This is a result of a significant contribution of both gas fuelled generators (54% of fossil production) and coal fuelled generators (46% of fossil production), in combination with high efficiencies of power plants but a low contribution of renewables (12% of total production). The carbon intensity of the electricity mix leads to an average CO_2 intensity per EV of 85 g/km. The freshwater usage is based on two scenarios, because no data was available about individual generators. In the negative scenario freshwater withdrawals per GWh are enormous because of the assumed large contribution of generators with once-through cooling systems using freshwater (46% of wet thermal production). In the positive scenario the withdrawals are very small as a result of a large contribution dry cooling systems (54% of wet thermal production). Water consumption per GWh is low in both scenarios because of a low contribution of generators with high water consumption, like hydroelectric and geothermal generators. Besides that, the consumption is almost similar in both scenarios because it can mainly be attributed to cooling towers, which are present in both scenarios, although for different fuels. Cooling towers account for 76% and 97% of the total freshwater consumption, in the negative and positive scenario, respectively. Table 22 displays the resulting local impact of EV usage in the Netherlands for both scenarios.

Table 22: Local impact of future EV usage in the Netherlands

Season	3,7% EV deployment (2020 target)			50% EV deployment		
	CO_2 emissions (kt)	Blue water withdrawal (Mm^3)	Blue water consumption (Mm^3)	CO_2 emissions (kt)	Blue water withdrawal (Mm^3)	Blue water consumption (Mm^3)
Negative scenario						
Winter	84	8,44	0,20	1.131	113,90	2,66
Spring	77	7,80	0,18	1.046	105,35	2,46
Summer	73	7,38	0,17	989	99,66	2,33
Fall	77	7,80	0,18	1.046	105,35	2,46
Annual	312	31,42	0,74	4.211	424,26	9,92
Positive scenario						
Winter	84	0,23	0,18	1.131	3,07	2,36
Spring	77	0,21	0,16	1.046	2,84	2,19
Summer	73	0,20	0,15	989	2,69	2,07
Fall	77	0,21	0,16	1.046	2,84	2,19
Annual	312	0,85	0,65	4.211	11,44	8,81

Table 23: Blue water impact of future EV usage relative to blue water characteristics in Netherlands

Season	3,7% EV deployment (2020 target)				50% EV deployment			
	Withdra. as share of natural runoff	Consump. as share of current footprint	Current water scarcity	Increase of water scarcity (%-point)	Withdra. as share of natural runoff	Consump. as share of current footprint	Current water scarcity	Increase of water scarcity (%-point)
Negative scenario								
Winter	0,22%	0,41%	1%	0,01%	2,99%	5,51%	1%	0,07%
Spring	0,25%	0,35%	2%	0,01%	3,38%	4,69%	2%	0,08%
Summer	0,43%	0,28%	4%	0,01%	5,86%	3,75%	4%	0,14%
Fall	0,31%	0,38%	2%	0,01%	4,12%	5,06%	2%	0,10%
Annual	0,28%	0,35%	2%	0,01%	3,80%	4,69%	2%	0,09%
Positive scenario								
Winter	0,01%	0,36%	1%	0,005%	0,08%	4,89%	1%	0,06%
Spring	0,01%	0,31%	2%	0,005%	0,09%	4,16%	2%	0,07%
Summer	0,01%	0,25%	4%	0,009%	0,16%	3,33%	4%	0,12%
Fall	0,01%	0,33%	2%	0,006%	0,11%	4,49%	2%	0,09%
Annual	0,01%	0,31%	2%	0,006%	0,10%	4,16%	2%	0,08%

The relations between the impact of future EV usage and the current blue water characteristics in the Netherlands for both scenarios are displayed in table 23. It can be seen that in the high water intensity of the electricity mix in the negative scenario has led to blue water withdrawals that are a significant share of the natural runoff, especially when 50% of the passenger car fleet is electric.

Interestingly, the consumption as share of the current footprint in both scenarios is significantly higher than in California and Rajasthan, while the average consumption per GWh in the Netherlands is lower. This is a result of the fact that the current average blue water footprint per person in the Netherlands is much lower than in the other two regions. In California the footprint is over 1500 m^3 per person, in Rajasthan over 300 m^3 and in the Netherlands under 100 m^3. Therefore, the relative contribution of water consumption for EVs is much larger in the Netherlands. However, because there is abundant natural blue water runoff in the Netherlands, the contribution of EV usage to water scarcity is only low. The CTA index remains below 5% in each season of the year. This is far below the threshold of 20% which is defined as the first indication of blue water scarcity by Hoekstra et al. (2012).

6. Discussion

6.1 Limitations of the methodology

The methodology proposed in this study provides a structured way to assess the local carbon and freshwater impact of using EVs. However, to make the methodology practical some assumptions are made. In particular, three assumptions about the electricity system can have a significant impact on the results. When implementing the methodology, one must be aware or these assumption and the limitations they put on the reliability of the results.

First of all, it is assumed that all electricity is produced locally. Although this is a fair assumption based on global averages for electricity import and export (Indexmundi, 2016), it might result in slightly unreliable results for individual regions. When there are indications that the electricity production in a region is not representative for the electricity consumption, more research about the exact origin of the consumed electricity in a region is necessary to account for this effect.

Secondly, only the local carbon and freshwater impact during operation of electricity generators are included in the methodology. The impacts of other activities in the process of electricity production, like resource extraction and facility construction, are not included. For the carbon impact this is a fair assumption because by far most emissions occur locally during the operational phase (Sathaye et al., 2011). For the water impact, however, the result can differ strongly when the production of biomass is included in the assessment. The production of biomass has a very high water impact when biomass is not derived as waste product from an existing industrial or agricultural process (Schornagel et al., 2012). This means that biomass has a high impact when crops are cultivated solely for the production of biomass. Because biomass does not have to be produced in the same region as where the electricity is produced, EV usage can even have an impact on other regions. In regions with a large share of biomass fired generators, more research about the origin of the biomass and the related water impact is recommended.

Finally, it is assumed that the electricity charged by EVs is the average of the total electricity mix in a region. This assumption might lead to an incorrect result when it is investigated more in detail what the marginal impact of extra electricity production is. It can be expected, for example, that the extra electricity production for EVs is in most cases peak load, which is often provided by other types of generators than base load (Graff Zivin et al., 2014). On the other hand, when smart charging is used and EVs are charged when electricity prices are low, it can be expected that more base load generators provide the electricity. More research about charging behaviour of EV users is necessary to account for this effect.

6.2 Reliability of the case study results

The reliability of the case study results depends on the quality of the input data. Most of the collected input data for the case studies is complete and of high quality. However, three uncertainties regarding the reliability of input data exist. Besides that, it is important to discuss the validity of the case study results. By doing that it can be assessed to what extend valid conclusions can be drawn about the individual cases, and to what extend results can be generalized to other regions.

Firstly, uncertainty exists about the water impact of hydropower. Estimates about the evaporation from hydropower reservoirs are complicated because of the multiple uses of reservoirs (e.g. water supply, recreation and flood control) and the different methods of allocating evaporation to electricity production (Macknick et al., 2011). Estimations in existing literature on the water consumption of hydropower differ from just over 5.000 m^3/GWh (Gleick, 1992) to almost 70.000 m^3/GWh (Torcellini et al., 2003). In this study a consumption of 17.000 m^3/GWh is used, based on the average of existing literature provided by Macknick et al. (2011). Although using this estimate seems to be the best way to approximate the water impact of hydropower, one must be careful with drawing conclusions when a considerable share of the water impact is caused by hydropower.

Secondly, data about the existing blue water characteristics in the investigated regions is uncertain because it is based on multiple assumptions. The study of Hoekstra et al. (2012) only provides data about the land area covered by river basins. Because none of the investigated regions is completely covered by river basins, assumptions had to be made to extrapolate the river basin data to the total land area of the region. Because the resulting water scarcities in this study are similar to the average water scarcities provided by A. Hoekstra (2016), it is assumed that they are representative for the actual situations in the investigated regions. However, the methodology did not allow identifying differences within a region, while differences might certainly exist. In California, for example, the south is more desolated than the north (A. Hoekstra, 2016). In Rajasthan the north-west is more desolated than the south-east (A. Hoekstra, 2016). Therefore, when implementing the methodology one must be aware that results for parts of the regions might be significantly different than the regional average.

Thirdly, uncertainty exists about the future characteristics regarding freshwater scarcity and the the electricity mix in the investigated regions. For the assessments it is assumed that the current characteristics of the investigated regions also apply to 2020 and to the year in which 50% EV deployment is achieved. However, water scarcities might change as a result of changing weather patterns and growing population (WEF, 2015). The carbon and freshwater intensity of the electricity mix might significantly change due to the replacement of old generators and the addition of new ones. For example, if Rajasthan would replace the once-through cooling system of the KST power plant by a cooling tower or dry cooling system, water withdrawals will decrease drastically. In California even a trend exists to replace once-through cooling systems because of the negative effect of warm discharge water on marine life (Averty et al., 2011). However, most once-through cooling systems in California use ocean water, having no impact at all at the blue water availability. Replacing these cooling systems will increase the blue water impact of the electricity mix. Besides that, it is expected that the share of renewables will increase strongly in the near future (Edenhofer et al., 2014). These developments will result in a lower carbon intensity of the electricity mix, but do not inherently decrease the water intensity of the electricity mix. Hydroelectric and geothermal generators, for example, consume much more water than most fossil fuelled generators (Macknick et al., 2011). More research about the expected changes in water scarcity and the electricity system in the investigated regions is necessary to account for this effect.

Finally, it is important to look at the validity of the case study results. The input data of the electricity mix in the Netherlands was uncomplete. As a result of the liberalization of the electricity market in the European Union, generator specific data has become commercially sensitive and only data about the electricity production per fuel was available. Therefore, only valid conclusions can be drawn about the carbon impact of EV usage in the Netherlands. The two outlined scenarios regarding freshwater characteristics of the electricity mix in the Netherlands can only be used to assess the general effect an electricity mix with high or low freshwater intensity. For California and Rajasthan valid conclusions can be drawn for the individual cases about both the carbon and the freshwater impact of EV usage. The case studies of California and Rajasthan, however, are not a good representation of every region in the world with water scarcity. Water scarcity in both California and Rajasthan is mainly a result of a very large water footprint of the agricultural sector, not a result of unusual low water availability (Growing Blue, 2011). Many regions exist with water scarcities similar to California and Rajasthan, but with less freshwater availability per capita, for example regions in West-Africa and Australia (Hoekstra et al., 2012). In these regions the relative impact of EV usage on the local freshwater scarcity can be much larger. Therefore, the results of the case studies of California and Rajasthan cannot be generalized to other regions without further research.

7. Conclusion

In this study the local freshwater and carbon impact of EV usage is investigated. A methodology is developed that provides the opportunity to assess the carbon and freshwater impact of EV usage for individual regions, based on local aspects regarding EV usage, electricity production and water scarcity. The methodology is demonstrated by implemented to three regions; California (United States), Rajasthan (India) and the Netherlands. In these regions the impact of both the targeted EV fleet for 2020 is investigated, as well as the hypothetical situation in which 50% of the total passenger car fleet is electric. At the end, the results of the case studies are used to draw general conclusions about the local freshwater and carbon impact of EV usage.

It can be concluded that the local freshwater impact of EV usage in most regions is small. Even when 50% of all passenger vehicles in California and Rajasthan is electric, the water consumption due to EV usage is less than 0,5% of the total annual blue water consumption in both regions. Therefore, the contribution of EV usage to more water scarcity in California and Rajasthan is only limited. However, the existing water scarcity in both regions is large. The water scarcity reaches over 100% during at least one month in the dry season in both regions. This means that during this month more water is consumed than naturally supplied, so all extra freshwater requirements have to be supplied in an artificial way. Only when this can be done in a sustainable and affordable way, EV usage will not become problematic. In the Netherlands EV usage will have no problematic freshwater impact at all. Even in the most negative scenario regarding the freshwater intensity of the Dutch electricity mix, the impact of EV usage is minimal due to low existing water scarcities.

The situation in California and Rajasthan, however, is not applicable to every region in the world with high water scarcity. In California and Rajasthan water scarcity is mainly a result of a very large water footprint of the agricultural sector. This minimalizes the relative addition of freshwater consumption due to EV usage. In regions having low existing freshwater footprints, however, the relative freshwater impact of EV usage will be much larger. Multiple of these regions exist worldwide which face severe existing water scarcities, like regions in West-Africa and Australia. A strong increase in EV deployment in these regions is expected to lead to a significant increase in the freshwater scarcity.

When the water requirements for EV usage are problematic in a region, it is important to decrease the water intensity of the electricity mix. However, the existing trends of modernizing the electricity system do not inherently lead to a smaller freshwater impact. The trend of replacing once-through cooling systems with cooling towers will increase the freshwater consumption in a region, and even the freshwater withdrawals when the original once-through cooling system made use of saline water. Also the trend of lowering the carbon impact of the electricity mix might increase the freshwater consumption, especially when fossil fuelled generators are replaced by hydroelectric or geothermal generators. Therefore, modernizing the electricity mix in a region does not inherently lead to a smaller freshwater impact of EV usage.

Finally, it can be concluded that the carbon impact of EV usage varies strongly per region. This is a result of regional differences in efficiency and composition of the electricity mix. The carbon intensity of newly sold conventional gasoline and diesel cars in Europe is on average 130 g/km. The carbon intensity of EVs is clearly lower in California and the Netherlands, with an average emission of only 44 g/km and 85 g/km, respectively. In Rajasthan, on the other hand, the average carbon intensity of EVs is currently 171 g/km. This is the result of a large contribution of inefficient coal power plants to the local electricity mix. Therefore, EVs have the potential to decrease the local carbon impact of passenger vehicles, but the emission reduction that can be achieved is largely dependent on the efficiency and composition of the local electricity mix.

8. References

ATS (2017). Amertech Tower Services. Cooling Tower Inspections. Retrieved 21-02-2017. Available on the World Wide Web: http://amertechtower.com/cooling-tower-inspections/

Averyt, K., Fisher, J., Huber-Lee, A., Lewis, A., Macknick, J., Madden, N., … Tellinghuisen, S. (2011). Freshwater Use by U.S. Power Plants: Electricity's Thirst for a Precious Resource. *Energy and Water in a Warming World Initiative - Union of Concerned Scientists*, 1–62. Retrieved from http://www.ucsusa.org/sites/default/files/attach/2014/08/ew3-freshwater-use-by-us-power-plants.pdf

Axsen, J., & Kurani, K. S. (2010). Anticipating plug-in hybrid vehicle energy impacts in California: Constructing consumer-informed recharge profiles. *Transportation Research Part D: Transport and Environment*, *15*(4), 212–219. http://doi.org/10.1016/j.trd.2010.02.004

Bayart, J. B., Bulle, C., Deschênes, L., Margni, M., Pfister, S., Vince, F., & Koehler, A. (2010). A framework for assessing off-stream freshwater use in LCA. *International Journal of Life Cycle Assessment*, *15*(5), 439–453. http://doi.org/10.1007/s11367-010-0172-7

BMW (n.d.). Verbruik Elektrische Auto. Retrieved 16-10-2016. Available on the World Wide Web: <http://store.bmw.nl/bmw-i3/verbruik-elektrische-auto/, http://store.bmw.nl/bmw-i3/range-extender/>

Bracmort K. (2011). Biomass feedstock for biopower: background and selected issues, report for congress; 2011. Retrieved July 10, 2011, from http://www.fas.org/sgp/crs/misc/R41440.pdf.

CBS (2017a). Centraal Bureau voor de Statistiek. Motorvoertuigenpark; inwoners, type, regio, 1 januari. Retrieved 23-01-2017. Available on the World Wide Web: http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=7374hvv&D1=2-11&D2=0&D3=a&HDR=T&STB=G2,G1&VW=T

CBS (2017b). Centraal Bureau voor de Statistiek. Verkeersprestaties motorvoertuigen; kilometers, voertuigsoort, grondgebied. Retrieved 10-12-2016. Available on the World Wide Web: http://statline.cbs.nl/Statweb/publication/?VW=T&DM=SLNL&PA=80302NED&D1=3-5&D2=1-6&D3=l&HD=151013-0836&HDR=T&STB=G1,G2

CBS (2017c). Centraal Bureau voor de Statistiek. Elektriciteit en warmte; productie en inzet naar energiedrager. Retrieved 03-01-2017. Available on the World Wide Web: http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=80030NED&D1=1&D2=a&D3=a&D4=l&VW=T

CBS (2017d). Centraal Bureau voor de Statistiek. Personal contact

CEA (2016). Central Electricity Authority. Government of India, Ministry of Power. Daily Reports. Retrieved 21-10-2016. Available on the World Wide Web: http://www.cea.nic.in/reports.html

CEC (2016). California Energy Commission. California Energy Almanac, Annual Generation – Plant Unit. Retrieved 21-10-2016. Available on the World Wide Web: http://www.energy.ca.gov/almanac/electricity_data/web_qfer/Annual_Generation-Plant_Unit.php

CEM (2016). Clean Energy Ministerial. Electric Vehicles Initiative (EVI). Retrieved 12-11-2016. Available on the World Wide Web: http://www.cleanenergyministerial.org/Our-Work/Initiatives/Electric-Vehicles

Chevrolet (2016). 2016 Chevrolet Volt Specifications. Retrieved 16-10-2016. Available on the World Wide Web: <http://media.chevrolet.com/media/us/en/chevrolet/vehicles/volt/2016.tab1.html#drive>

Coffman, M., Bernstein, P., & Wee, S. (2015). Factors Affecting EV Adoption : A Literature Review and EV Forecast for Hawaii, (April 2015), 1–36. Retrieved from http://evtc.fsec.ucf.edu/publications/documents/HNEI-04-15.pdf

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Minx, J. C., Farahani, E., Susanne, K., … Zwickel, T. (2014). *Climate Change 2014: Mitigation of Climate Change*. *Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. http://doi.org/10.1017/CBO9781107415416

Edwards, R., Hass, H., Larivé, J.-F., Lonza, L., Mass, H., Rickeard, D., … Weindorf, W. (2013). *Well-to-Wheels analysis of future automotive fuels and powertrains in the European context WELL-TO-TANK (WTT) Report. Version 4. Joint Research Center of the EU (JRC): Ispra, Italy*. http://doi.org/10.2790/95629

EIA (2016a). U.S. Energy Information Administration. *International Energy Outlook 2016*. *International Energy Outlook 2016* (Vol. 0484(2016)). http://doi.org/www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf

EIA, 2016b. U.S. Energy Information Administration. Carbon Dioxide Emissions Coefficients. Retrieved 03-02-2017. Available on the World Wide Web: https://www.eia.gov/environment/emissions/co2_vol_mass.cfm

Falkenmark, M., A. Berntell, A. Jägerskog, J. Lundqvist, M. Matz, and H. Tropp (2007). On the verge of a new water scarcity: A call for good governance and human ingenuity, *SIWI policy brief*, Stockholm Int. Water Inst., Stockholm.

FHWA (2016). Federal Highway Administration. State & Urbanized Area Statistics. Retrieved 10-12-2016. Available on the World Wide Web: https://www.fhwa.dot.gov/ohim/onh00/onh2p11.htm

Fleetcarma (2014). Electric Range for the Nissan Leaf & Chevrolet Volt in Cold Weather. Retrieved 16-01-2017. Available on the World Wide Web: http://www.fleetcarma.com/nissan-leaf-chevrolet-volt-cold-weather-range-loss-electric-vehicle/

Gleick, P. H. (1996). Water resources. In Encyclopedia of Climate and Weather, ed. by S. H. Schneider, Oxford University Press, New York, vol. 2, pp.817-823. Retrieved from: http://water.usgs.gov/edu/watercyclefreshstorage.html

Global Reporting Initiative (2010). Reporting framework downloads. Retrieved 06-10-2016. Available on the World Wide Web: http://www.globalreporting.org/Home

Graff Zivin, J. S., Kotchen, M. J., & Mansur, E. T. (2014). Spatial and temporal heterogeneity of marginal emissions: Implications for electric cars and other electricity-shifting policies. *Journal of Economic Behavior and Organization*, *107*(PA), 248–268.

http://doi.org/10.1016/j.jebo.2014.03.010

Growing Blue. (2011). Water. Economics. Life., 36. Retrieved from http://growingblue.com/wp-content/uploads/2011/04/Growing-Blue.pdf

Helms, H., Pehnt, M., Lambrecht, U., & Liebich, A. (2010). Electric vehicle and plug-in hybrid energy efficiency and life cycle emissions. *18th International Symposium Transport and Air Pollution, Session*, *3*, 113. http://doi.org/http://ifeu.de/verkehrundumwelt/pdf/Helms%20et%20al.%20(2010)%20Electric%20vehicles%20(TAP%20conference%20paper)%20final.pdf

Hoekstra, A. (2016). Four Billion People Experience Water Scarcity, (February), 1–7. Retrieved from http://therealnews.com/t2/about-us/index.php?option=com_content&task=view&id=767&Itemid=74&jumival=15718

Hoekstra, A. Y. (2016). A critique on the water-scarcity weighted water footprint in LCA. *Ecological Indicators*, *66*, 564–573. http://doi.org/10.1016/j.ecolind.2016.02.026

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The Water Footprint Assessment Manual*. *Febrero 2011*. http://doi.org/978-1-84971-279-8

Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., & Richter, B. D. (2012). Global monthly water scarcity: Blue water footprints versus blue water availability. *PLoS ONE*, *7*(2). http://doi.org/10.1371/journal.pone.0032688

Hussy, C., Klaasen, E., Koornneef, J., & Wigand, F. (2014). International Comparison of Fossil Power Efficiency and CO_2 Intensity. *Ecofys*, 1–84.

Indexmundi (2016). Electricity - imports – World. Retrieved 01-10-2016. Available on the World Wide Web: http://www.indexmundi.com/map/?v=83

IDA (2016). International Desalination Association. IDA Desalination Yearbook 2016-2017. Retrieved 09-12-2016. Available on the World Wide Web: https://www.paperturn.com/flipbook/id/ida-yb_free/ida-desalination-yearbook-2016-2017?pid=NzU7549#/19

Idtechex (2015). Hybrid vehicle range extenders: goodbye pistons. Retrieved 16-10-2016. Available on the World Wide Web: <http://www.idtechex.com/research/articles/hybrid-vehicle-range-extenders-goodbye-pistons-00007552.asp?donotredirect=true>

IEA (2016). Internation Energy Agency. Global EV Outlook 2016 Electric Vehicles Initiative. *Iea*.

IndiaOnline (2016a). Population of India 2017. Retrieved 12-11-2016. Available on the World Wide Web: http://www.indiaonlinepages.com/population/india-current-population.html

IndiaOnline (2016b). Population of Rajasthan 2017. Retrieved 12-11-2016. Available on the World Wide Web: http://www.indiaonlinepages.com/population/rajasthan-population.html

INL (2015). Idaho National Laboratory. Plugged In: How Americans Charge Their Electric Vehicles. Findings from the largest plug-in electric vehicle infrastructure demonstration in the world. Retrieved 07-12-2016. Available on the World Wide Web: https://avt.inl.gov/sites/default/files/pdf/arra/SummaryReport.pdf

Kessler, J., & Knight, E. (2005). Environmental Issues and Opportunities in the California – Mexico

Border Region, (May).

King, C. W., & Webber, M. E. (2007). The Water Intensity of the Hydrogen Economy. *Journal Of Energy*, *42*(12), 1–12.

Kintner-Meyer, M., Schneider, K., & Pratt, R. (2007). Impacts Assessment of Plug-in Hybrid Vehicles on electric utilities and regional U.S. Power Grids. *Federal Energy Regulatory Commission*, 1–20. http://doi.org/10.1017/CBO9781107415324.004

Kundzewicz, Z. W., L. J. Mata, N. W. Arnell, P. Döll, P. Kabat, B. Jiménez, K. A. Miller, T. Oki, Z. Sen, and I. A. Shiklomanov (2007). Freshwater resources and their management, in Climate Change 2008: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by L. Parry et al., pp. 173–210, Cambridge Univ. Press, Cambridge, U. K.

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2011). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environmental Research Letters*, *7*(4), 45802. http://doi.org/10.1088/1748-9326/7/4/045802

Mekonnen, M. M., Gerbens-Leenes, P. W., & Hoekstra, A. Y. (2015). The consumptive water footprint of electricity and heat: a global assessment. *Environ. Sci.: Water Res. Technol.*, *1*(3), 285–297. http://doi.org/10.1039/C5EW00026B

Ministry of Road Transport and Highways (2011). Road Transport Yearbook (2011-12). Retrieved 07-01-2017. Available on the World Wide Web: http://in.tool-alfa.com/LinkClick.aspx?fileticket=RhX00HSiIT4%3D&tabid=72&mid=486

Moomaw, W., Burgherr, P., Heath, G., Lenzen, M., Nyboer, J., & Verbruggen, A. (2011). Annex II: Methodology. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, *16*(10), NP. http://doi.org/10.1093/ntr/ntt227

Nissan (n.d.). Een nieuwe aanpak van autorijden. Retrieved 16-10-2016. Available on the World Wide Web: <https://www.nissan.nl/voertuigen/nieuw/leaf.html?&cid=psmvAMueTgE_dc|D).>

PEV Collaborative (2016): Plug-In Electric Vehicle Collaborative. Cumulative Sales. Retrieved 16-10-2016. Available on the World Wide Web: http://www.pevcollaborative.org/sites/all/themes/pev/files/12_dec_PEV_cumulative_0.pdf

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the environmental impacts of freshwater consumption in LCA. *Environmental Science and Technology*, *43*(11), 4098–4104. http://doi.org/10.1021/es802423e

Power Engineering (2014): The Flexibility of Internal Combustion Engines. Retrieved 21-12-2016. Available on the World Wide Web: http://www.power-eng.com/articles/print/volume-118/issue-9/features/the-flexibility-of-internal-combustion-engines.html

RVO (2017). Rijksdienst voor Ondernemend Nederland. Cijfers elektrisch vervoer. Retrieved 21-01-2017. Available on the World Wide Web: http://www.rvo.nl/onderwerpen/duurzaam-ondernemen/energie-en-milieu-innovaties/elektrisch-rijden/stand-van-zaken/cijfers

Sathaye, J., Lucon, O., Rahman, A., Christensen, J., Denton, F., Fujino, J., … Shmakin, A. (2011). Renewable Energy in the Context of Sustainable Development. *IPCC Special Report on*

Renewable Energy Sources and Climate Change Mitigation, 707–790.

Schornagel, J., Niele, F., Worrell, E., & Böggemann, M. (2012). Water accounting for (agro)industrial operations and its application to energy pathways. *Resources, Conservation and Recycling*, *61*, 1–15. http://doi.org/10.1016/j.resconrec.2011.12.011

Steinhilber, S., Wells, P., & Thankappan, S. (2013). Socio-technical inertia: Understanding the barriers to electric vehicles. *Energy Policy*, *60*, 531–539. http://doi.org/10.1016/j.enpol.2013.04.076

Tennet (2017). Personal contact

Tesla (n.d.). Model S Specifications. Retrieved 16-10-2016. Available on the World Wide Web: <https://www.teslamotors.com/nl_NL/models?redirect=no>

Torcellini, P.; Long, N.; Judkoff, R. (2003). *Consumptive Water Use for U.S. Power Production.* NREL/TP-550-33905. Golden, CO: National Renewable Energy Laboratory, 2003.

Transport & Environment (2016). How clean are Europe's cars? An analysis of carmaker progress towards EU CO2 targets in 2014. Retrieved 07-02-2017. Available on the World Wide Web: https://www.transportenvironment.org/what-we-do/cars-and-co2

Tsiourtis, N. X. (2001). Desalination and the environment. *Desalination*, *141*(3), 223–236. http://doi.org/10.1016/S0011-9164(01)85001-3

UCS (2016). Union of Concerned Scientists. How it Works: Water for Power Plant Cooling. Retrieved 21-12-2016. Available on the World Wide Web: http://www.ucsusa.org/clean-energy/energy-and-water-use/water-energy-electricity-cooling-power-plant#.WKr8Cm8rLIV

UNFCCC (2015): United Nations Framework Convention on Climate Change. Paris Declaration on Electro-Mobility and Climate Change and Call to Action Electrifying Sustainable Transport. Retrieved 16-10-2016. Available on the World Wide Web: http://newsroom.unfccc.int/lpaa/transport/the-paris-declaration-on-electro-mobility-and-climate-change-and-call-to-action

US Climate Data (2017). Climate California – Sacramento. Retrieved 01-02-2017. Available on the World Wide Web: http://www.usclimatedata.com/climate/california/united-states/3174

USGS (2016a). United States Geological Survey's Water Science School. Saline Water Use in the United States. Retrieved 01-02-2017. Available on the World Wide Web: https://water.usgs.gov/edu/salineuses.html

USGS (2016b). United States Geological Survey's Water Science School. Wastewater Treatment; what is wastewater, and why treat it? Retrieved 04-12-2016. Available on the World Wide Web: https://water.usgs.gov/edu/wuww.html

van Weert, F., van der Gun, J., & Reckman, J. (2009). Global Overview of Saline Groundwater Occurrence and Genesis. *Igrac*, (July), 26–27.

Wada, Y., Van Beek, L. P. H., Viviroli, D., Drr, H. H., Weingartner, R., & Bierkens, M. F. P. (2011). Global monthly water stress: 2. Water demand and severity of water stress. *Water Resources Research*, *47*(7), 1–17. http://doi.org/10.1029/2010WR009792

Wärtsilä (2016). Combustion Engine for Power Generation: Introduction. Retrieved 21-12-2016. Available on the World Wide Web: http://www.wartsila.com/energy/learning-center/technical-comparisons/combustion-engine-for-power-generation-introduction

Weerstatistieken (2017). Maandgemiddelde temperaturen. Retrieved 01-02-2017. Available on the World Wide Web: https://weerstatistieken.nl/

WEF (2015). World Economic Forum. *Global Risks 2015, 10th Edition*. World Economic Forum

World Weather Online (2017). Jaipur, Rajasthan Monthly Climate Average, India. Retrieved 01-02-2017. Available on the World Wide Web: https://www.worldweatheronline.com/jaipur-weather-averages/rajasthan/in.aspx

Worldbank (2014). Electric power transmission and distribution losses (% of output). Retrieved 10-01-2017. Available on the World Wide Web:http://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?year_high_desc=false

Yong, J. Y., Ramachandaramurthy, V. K., Tan, K. M., & Mithulananthan, N. (2015). A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. *Renewable and Sustainable Energy Reviews*, *49*, 365–385. http://doi.org/10.1016/j.rser.2015.04.130

Yuksel, T., & Michalek, J. J. (2015). Effects of regional temperature on electric vehicle efficiency, range, and emissions in the united states. *Environmental Science and Technology*, *49*(6), 3974–3980. http://doi.org/10.1021/es505621s

ZEV working Group (2016). Governor’s Interagency Working Group on Zero-Emission Vehicles. 2016 ZEV ACTION PLAN. Retrieved 20-10-2016. Available on the World Wide Web: https://www.gov.ca.gov/docs/2016_ZEV_Action_Plan.pdf

Appendix A – Electricity mix California

Table 24: Electricity mix in California in annual production per primary fuel, generation technology, cooling system and water type

Input fuel	Generation technology	Cooling system	Water type	Net production (GWh/year)
Non-thermal generation				
Water	Wind turbine			17.642
Sun (PV)	Photovoltaic cells			15.212
Wind	Hydroelectric generator			12.835
Total non-thermal generation				**45.689**
Dry thermal generation				
Natural gas	Combustion turbine			16.093
Biomass	Combustion turbine			1.577
Oil	Combustion turbine			54
Total dry thermal generation				**17.724**
Wet thermal generation				
Natural gas	Combined cycle	Tower	Fresh	60.611
		Once-through	Saline	6.162
			Fresh	324
		Dry	Fresh	2.858
	Steam turbine	Once-through	Saline	5.818
			Fresh	169
		Tower	Fresh	536
	No data			33.721
Nuclear	General	Once-through	Saline	18.525
Coal	General	Tower	Fresh	12.375
Geothermal	Dry steam	Tower	Fresh	5.866
	Binary	Tower	Fresh	222
	No data			6.369
Biomass	Biogas	Tower	Fresh	2.185
		Dry	Fresh	555
	No data			2.044
Sun (CSP)	CSP Trough	Tower	Fresh	615
	No data			1.832
Other	No data			189
Total wet thermal production				**161.185**
Total in California				224.599

References: Can be found in the accompanying Excel file.

Appendix B – Electricity mix Rajasthan

Table 25: Electricity mix in Rajasthan in annual production per power plant, input fuel, generation technology, cooling system and water type

Power plant	Input fuel	Generation technology	Cooling technology	Water type	Net production (GWh)				
					Winter	Spring	Summ.	Fall	Annual
Non-thermal production									
Wind turbines (total installed capacity)	Wind	Wind turbine			851	1.902	1.899	676	5.328
Solar power (PV) (total installed capacity)	Solar	Photovoltaic cells			520	579	506	512	2.117
Hydropower (total installed capacity)	Hydro	Hydroelectric generator			381	8	216	383	988
Total non-thermal production					1.752	2.489	2.621	1.571	8.433
Thermal production									
Kawai Thermal Power Station	Coal	Supercritical	Tower	Fresh	2.388	2.475	2.324	1.285	8.472
Kota Super Thermal Power Plant	Coal	Subcritical	Once-through	Fresh	2.178	2.078	1.385	2.445	8.085
Rajasthan Atomic Power Station	Nuclear	Generic	Tower	Fresh	2.076	1.867	1.817	1.620	7.380
JSW Barmer Jalipa Kapurdi Power Station	Coal	Subcritical	Tower	Fresh	1.887	1.633	1.576	1.843	6.940
Chhabra Thermal Power Plant	Coal	Subcritical	Tower	Fresh	1.414	1.619	1.360	1.985	6.378
Kalisindh Thermal Power Station	Coal	Subcritical	Tower	Fresh	2.149	1.764	580	1.522	6.015
Suratgarh Super Thermal Power Plant	Coal	Subcritical	Tower	Fresh	1.536	1.632	951	1.412	5.531
Ramgarh Gas Thermal Power Station	Natural Gas	Combined cycle	Tower	Fresh	359	367	328	332	1.386
Barsingsar Thermal Power Station	Coal	Subcritical	No data			325	210	350	415
Anta Thermal Power Station	Natural Gas	Combined cycle	No data			66	114	316	145
Biomass power plants (total installed capacity)	Biomass	No data					67	75	70
Dholpur Combined Cycle Power Station	Natural Gas	Combined cycle	No data			67	109	16	-
Giral Lignite Power Plant	Coal	Subcritical	Tower	Fresh	21	-	-	-	21
Total thermal production					14.532	13.944	11.074	13.063	52.613
Total in Rajasthan					16.284	16.433	13.695	14.634	61.046

References: Can be found in the accompanying Excel file.

Appendix C – Electricity mix The Netherlands

Table 26: Negative scenario of the electricity mix in The Netherlands in annual production per input fuel, generation technology, cooling system and water type

Power plant	Input fuel	Generation technology	Cooling technology	Water type	Net production (GWh/year)
Non-thermal production					
Wind turbines (total installed capacity)	Wind	Wind turbine			7.489
Solar power (PV) (total installed capacity)	Solar	Photovoltaic cells			1.108
Hydropower (total installed capacity)	Hydro	Hydroelectric generator			93
Total non-thermal production					**8.690**
Dry thermal production					
Oil power (total installed capacity)	Oil	Combustion turbine			77
Total dry thermal production					**77**
Wet thermal production					
Gas power (total installed capacity)	Natural gas	Average	Tower	Fresh	46.163
Coal power (total installed capacity)	Coal	Average	Once-through	Fresh	38.864
Biopower (total installed capacity)	Biomass	Average	Tower	Fresh	4.967
Nuclear power (total installed capacity)	Nuclear	Average	Once-through	Fresh	4.078
Other (total installed capacity)	Other				7.163
Total wet thermal production					**101.235**
Total in the Netherlands					110.002

References: Can be found in the accompanying Excel file.

Table 27: Positive scenario of the electricity mix in The Netherlands in annual production per input fuel, generation technology, cooling system and water type

Power plant	Input fuel	Generation technology	Cooling technology	Water type	Net production (GWh/year)
Non-thermal production					
Wind turbines (total installed capacity)	Wind	Wind turbine			7.489
Solar power (PV) (total installed capacity)	Solar	Photovoltaic cells			1.108
Hydropower (total installed capacity)	Hydro	Hydroelectric generator			93
Total non-thermal production					**8.690**
Dry thermal production					
Oil power (total installed capacity)	Oil	Combustion turbine			77
Total dry thermal production					**77**
Wet thermal production					
Gas power (total installed capacity)	Natural gas	Average	Dry	Fresh	46.163
Coal power (total installed capacity)	Coal	Average	Tower	Fresh	38.864
Biopower (total installed capacity)	Biomass	Average	Dry	Fresh	4.967
Nuclear power (total installed capacity)	Nuclear	Average	Tower	Fresh	4.078
Other (total installed capacity)	Other				7.163
Total wet thermal production					**101.235**
Total in Rajasthan					110.002

References: Can be found in the accompanying Excel file.

Appendix D – Seasonal water characteristics of the investigated regions

Table 28: Seasonal water characteristics of the water basins covering California

Basin	Land area (km^2)	Area inside region	Blue water (Mm^3)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Salinas	12.656	100%	Nat runoff	12	34	59	37	33	47	66	68	43	10	3	2
			Footprint	2	2	2	8	25	52	83	88	55	11	3	2
San Joaquin River	34.366	100%	Nat runoff	707	829	1.286	1.335	1.137	1.099	1.268	1.194	818	322	75	102
			Footprint	8	10	93	399	659	1.063	1.460	1.560	1.113	379	67	14
Sacramento River	77.289	98%	Nat runoff	5.376	6.127	6.249	5.068	3.137	2.369	2.064	1.708	1.170	511	344	1.439
			Footprint	15	15	49	288	668	1.236	1.592	1.566	1.081	300	41	16
Eel River	7.458	100%	Nat runoff	1.366	1.258	927	541	304	174	105	64	39	23	16	580
			Footprint	0	0	0	0	1	1	1	1	1	0	0	0
Klamath River	40.099	66%	Nat runoff	3.011	3.574	3.546	3.046	2.002	1.051	699	456	276	147	395	1.495
			Footprint	1	1	1	29	82	128	176	152	93	29	2	1
Rogue River	14.550	2%	Nat runoff	1.090	1.088	909	858	623	302	190	120	73	42	212	514
			Footprint	1	1	1	4	12	20	27	23	15	5	1	1
Colorado River	640.636	2%	Nat runoff	323	100	738	3.046	5.904	4.320	2.391	1.654	1.127	740	370	231
			Footprint	52	79	259	465	689	834	869	785	599	367	153	88
Total of basins in region	166.604	100%	Nat runoff	9.361	10.502	10.757	8.947	5.968	4.403	3.960	3.324	2.245	964	701	3.095
			Footprint	26	28	147	715	1.401	2.421	3.229	3.292	2.297	709	114	33
Total California	409.617	100%	Nat runoff	16.188	18.161	18.603	15.473	10.320	7.614	6.848	5.748	3.882	1.667	1.212	5.353
			Footprint	46	48	254	1.237	2.423	4.186	5.585	5.693	3.972	1.226	196	57
			Water scarcity	0%	0%	1%	8%	23%	55%	82%	99%	102%	74%	16%	1%

Reference: Hoekstra et al. (2012)

Table 29: Seasonal water characteristics of the water basins covering Rajasthan

Basin	Land area (km^2)	Area inside region	Blue water (Mm^3)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mahi River	36.152	47%	Nat runoff	884	158	246	223	137	38	2.641	4.427	3.152	1.389	866	574
			Footprint	235	213	332	302	186	51	25	40	81	152	128	146
Ganges	1.022.583	10%	Nat runoff	32.182	10.982	6.447	2.897	2.922	7.824	8.625	28.520	6.973	7.842	2.622	9.626
			Footprint	13.159	14.045	19.911	12.436	10.053	5.544	3.942	2.382	3.662	7.534	11.330	6.755
Indus	1.138.091	12%	Nat runoff	1.919	9.643	8.198	1.870	8.514	8.265	2.379	40.736	1.344	9.300	0.859	6.757
			Footprint	6.455	7.692	4.959	3.808	6.182	6.262	8.796	13.191	6.069	3.121	7.129	3.924
Total of basins in region	257.555	100%	Nat runoff	5.092	2.345	3.972	4.049	3.605	5.024	3.062	19.928	5.021	7.797	5.000	3.060
	341.901	100%	Footprint	5.926	2.729	4.622	4.712	4.195	5.847	5.201	23.191	7.481	9.074	5.818	3.561
Total Rajasthan			Nat runoff	1.185	546	924	942	839	1.169	3.040	4.638	3.496	1.815	1.164	712
			Footprint	2.577	2.843	4.618	3.565	2.148	1.559	1.714	2.159	2.737	2.813	2.399	1.422
			Water scarcity	43%	104%	100%	76%	51%	27%	11%	9%	16%	31%	41%	40%

Reference: Hoekstra et al. (2012)

Table 30: Seasonal water characteristics of the water basins covering the Netherlands

Basin	Land area (km^2)	Area inside region	Blue water (Mm^3)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rhine	191.145	6,6%	Nat runoff	13.179	7.658	8.094	9.602	8.013	6.055	4.780	4.184	3.972	4.515	6.547	8.364
			Footprint	122	122	122	123	135	140	146	176	150	125	122	122
Schelde	21.575	0,1%	Nat runoff	1.352	706	604	472	285	169	112	80	55	64	373	746
			Footprint	29	29	29	29	32	34	37	39	32	29	29	29
Total of basins in region	12.650	100%	Nat runoff	872	507	535	635	530	400	316	277	263	298	433	553
			Footprint	8	8	8	8	9	9	10	12	10	8	8	8
Total the Netherlands	37.666	100%	Nat runoff	1.734	1.008	1.065	1.263	1.054	796	628	550	522	593	861	1.100
			Footprint	16	16	16	16	18	18	19	23	20	16	16	16
			Water scarcity	1%	2%	2%	1%	2%	2%	3%	4%	4%	3%	2%	1%

Reference: Hoekstra et al. (2012)